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REVIEW OF STUDIES OF TRAPPED RADIATION WITH SATELLITE-BORNE APPARATUS

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1. Introduction

The magnetic field of the earth is bounded at radial distances of about ten earth radii by its contact with interplanetary space (CAHILL and AMAZEEN, 1962). Confined within the geomagnetic field are many energetic charged particles, mainly electrons and protons, which, spiralling around magnetic lines of force, bounce between mirror points in the two hemispheres, and drift in longitude around the earth. If they mirror too low in the atmosphere, they may be absorbed. Thus the region of quasi-constant confinement or trapping extends from altitudes of some hundreds of kilometers out to about 50 000 to 100 000 kilometers, from the substantial atmosphere out to interplanetary space. This vast region is called the radiation zone of geomagnetically-trapped particles.

The radiation zone was discovered unexpectedly when the geiger tubes of the first two U.S. satellites 1958α and 1958γ, Explorer I and Explorer III, respectively, counted at high altitudes at rates far *less* than would be expected even from the relatively low intensity cosmic radiation alone (VAN ALLEN, 1958; VAN ALLEN *et al.*, 1958).

By observation of the same effect with two satellites, by laboratory calibrations of similar apparatus, and by a logical exclusion of other reasonable explanations, the Iowa group felt justified in announcing that the low *apparent* counting rate of the geiger tubes was actually a very high *true* rate, caused by high fluxes of geomagnetically-confined charged particles. Later studies showed that this interpretation was correct, and that Explorer I and Explorer III had penetrated into the lower regions of the radiation zone.

The very first studies set a pattern for many of the later investigations, summarized by saying that the experimentalists found that their apparatus behaved in an unexpected manner. By careful experimental techniques they concluded they had discovered a new phenomenon. The theorists were then faced with the problem of accepting the experimental results as valid and then trying to explain the new phenomenon, or alternatively rejecting the experimental conclusions as unjustified and/or invalid. Similar choices are still being made as studies of the radiation zone continue. It is one purpose of this review to assist in making these choices with a general critical assessment of the experimental data.

Parameters involved in studies of the geomagnetically trapped radiation are discussed in Section 2, where it is shown what information is required in order to describe the characteristics of the radiation completely. The "natural" system of magnetic coordinates introduced by MCILWAIN (1961) is used as a convenient means of obtaining this description.

An historical outline of the advance to the present knowledge is then given briefly in Section 3. Relevant experiments made from 1957 to 1961 are tabulated as an intrinsic part of this historical review. The principal scientific and technical references for each experiment are listed, together with an indication of the energy ranges and types of the detectable particles but without technical details such as electronic circuitry. Only experiments successfully launched are included, and the orbital characteristics are summarized.

An attempt is made in Sections 4 and 5 to present briefly the current experimental knowledge of the radiation zones. Since the author began to write this review, the radiation environment changed greatly when a nuclear device was exploded at a high altitude on July 9, 1962 creating an intense artificial radiation belt (O'BRIEN *et al.* 1962c). To simplify discussion and review, this radiation belt is treated separately in Section 6.

For convenience, a single Section (7) is given to listing revised interpretations of data, proceeding chronologically from satellite to satellite. In many cases, these revisions have been made by the original authors, and these are included for completeness. In other cases, we have assessed the published data ourselves, and then rendered a judgment which is undoubtedly partially subjective. In these cases, only brief justification of the judgments is attempted.

Many ground based observations have yielded important information about the radiation zones, and these are included in Section 8. In Section 9 a few of the requirements for an ideal experimental study of the radiation zones are given.

An original aim of this review was quite simply to provide for experimentalists a comprehensive set of references and very brief descriptions of experiments which have studied the radiation zones, and to provide for theoreticians a review of some measurements which have been misinterpreted. The modification of the radiation zones by the production of the durable artificial radiation belt has given added importance to such a review, since it is now impossible to measure the electron spectrum of the natural inner zone, for example, and it will remain impossible for years to come, even if no further artificial belts are created. In spite of this, and in spite of the resultant reduction in the time spent in writing this review, we have attempted to abide largely by our original aims. We are not at all confident that this review will not be made out of date by other military activity before it is even published.*

This review lacks coherence because its subject matter lacks coherence. Apart from the unifying concept of the Lorentz force governing the detailed motion of the particles, there is no satisfying theoretical grasp of the phenomena involved. The field is one of rich discoveries for the experimentalist, but no one has succeeded in placing all the jewels in the proper setting. As will be seen in the following, some of the jewels are actually synthetic, and their rejection is necessary. But as yet, the remainder are rough-cut or merely baubles, and their true value is difficult to assess. This review then, is largely a catalogue of numbers and measurements.

2. Parameters of the Geomagnetically Trapped Radiation

2.1 FORMULATION OF THE PROBLEM

The ultimate purpose of radiation zone measurements is to determine completely the

* *Note added in proof:* This pessimism was validated by the high-altitude nuclear tests of the USSR on October 22, October 28, and November 1, 1962, which produced transient artificial belts. (W. BROWN, *Aviation Week*, Feb. 4, 1963).

characteristics of the geomagnetically trapped radiation. Following VAN ALLEN (1962), these characteristics can be described with the use of the following parameters:

j_i The unidirectional intensity (e.g., in units of particles (cm^2 sec sterad)$^{-1}$) of particles of type i having energies between E and $E + dE$.

r, ψ, θ The geographic polar coordinates of an arbitrary point in the vicinity of the earth.

l, m, n The direction cosines of the direction in space being considered.

E Particle kinetic energy.

t Time.

Thus, the problem may be said to be the determination of the functions j_i ($r, \psi, \theta, l, m, n, E, t$) where i denotes successively electrons, protons, alpha particles, and any other charged particles or ions.

Continuing with VAN ALLEN's summary but extending its applicability in the time-stationary state, the application of trapping theory (see Section 2.2) greatly simplifies the observational task, as follows:

(a) At any point the radiation is essentially cylindrically symmetric with respect to the magnetic field vector **B**. Thus all particle directions which make a (pitch) angle α with respect to **B** are equivalent.

(b) A given geomagnetic shell is defined by the integral adiabatic invariant I and labelled by a single parameter L (see Section 2.2). On such a shell the complete positional and angular dependence of j_i is contained within the dependence of j_i on the angle α_0 to **B** at the position on the shell at which **B** has its minimum value B_0 gauss (i.e. on the magnetic equator).

Hence the complete observational problem for the time-stationary state is reduced to that of determining

$$j_i\,(L, \alpha_0, E) \ldots \textit{Description A.}$$

Thus the perfect experiment on the perfect space-probe would be one which measured the angular distribution and the energy spectrum of charged particles of all types as the vehicle moved radially outwards in the plane of the geomagnetic equator. However, since the radiation zones are certainly not unchanging in time or local time, even a number of such perfect experiments would not complete our experimental solution of the problem.

Another method of approaching a complete measurement involves the omni-directional particle intensity J (e.g., in units of particles (cm^2 sec)$^{-1}$),

$$J_i = 2\pi \int_0^{\pi} j_i \sin \alpha \, d\alpha.$$

Following RAY (1960), if one has measured J_i as a function of position or B/B_0 on a given magnetic shell L, then

$$J_i\left(\frac{B}{B_0}\right) = 4\pi\left(\frac{B}{B_0}\right) \int_{\cos\alpha_0}^{1} d\cos\alpha_0' \frac{\cos\alpha_0'}{\sqrt{1 - \frac{B}{B_0}\sin^2\alpha_0'}}\, j_i(\alpha_0')$$

Thus an alternative complete description in the timestationary state is

$$J_i\ (L, B/B_0, E)$$

which we may write as

$$J_i\ (L, B, E) \ldots \textit{Description B.}$$

If one then attempted a perfect experiment to obtain description *B*, the vehicle would have to have such an orbit that in time it passed through all positions of a set of (*L*, *B*).

Briefly then, for description *A*, it is the role of the vehicle to move through all values of *L* in the geomagnetic equatorial plane, and the role of the experiment to measure the directional intensity and energy spectrum as a function of pitch angle and particle type as it does so. For description *B*, it is the role of the vehicle to cover an extensive network of (*L*, *B*) points, and the role of the experiment to measure the omnidirectional intensity as a function of particle type and energy as it does so.

It is one purpose of this note to review the compromises which have been made in attempts to attain these perfect experiments in an imperfect world.

Because of the payload weight and/or power limitations, and orbital or trajectory limitations, the complete descriptions *A* and *B* have not been attempted even in the time-stationary state. Instead, the experiments performed to date fall into three main categories (as discussed by McIlwain, 1960b, for example):

(1) a crude exploratory investigation of the gross nature, intensity, and spatial distribution of particles in a region;

(2) a more discriminating experiment approaching descriptions A or B above in the time-stationary state, perhaps for a give particle type and region of space, and

(3) temporal and spatial monitoring of various broad classifications of particles,

2.2 THE "NATURAL" GEOMAGNETIC COORDINATES *L* AND *B*

As outlined above, use of the "natural" geomagnetic coordinates *L* and *B* greatly facilitates study of the geomagnetically trapped radiation. For a detailed discussion of the derivation of the system and a description of its applications, see McIlwain (1961) and also Van Allen (1962). The only force (**F**) acting on the particle of charge q moving with velocity **v** in a magnetic field **B** is taken to be the Lorentz force $\mathbf{F} = q\ [\mathbf{v} \times \mathbf{B}]$.

In the Alven approximation, the magnetic moment μ of a charged particle spiralling along a geomagnetic field line is a constant. Accordingly,

$$\mu = \frac{p_\perp^2 \sqrt{1-\beta^2}}{2\,mB} = \text{constant}\,,$$

where $p_\perp = p \sin \alpha$, the component of particle momentum perpendicular to **B**,

$\beta = v/c$, where v = velocity of the particle, and m = particle mass. Accordingly,

$$\mu = \frac{p^2 \sqrt{1-\beta^2}}{2m} \frac{\sin^2 \alpha}{\mathrm{B}} = \text{constant}\,,$$

whence

$$\frac{\sin^2 \alpha}{B} = \text{constant}\,.$$

As a consequence, a geomagnetically trapped particle executes an oscillatory motion between two mirror or reflecting points M and M^* in opposite hemispheres where the scalar magnetic field strength is B_{m}, where

$$\frac{\sin^2 \alpha}{B} = \frac{1}{B_{\mathrm{m}}}\,.$$

Furthermore, another invariant of the particle motion is the longitudinal integral inva riant I where

$$I = \int_{M^*}^{M} \sqrt{1 - B/B_{\mathrm{m}}}\, \mathrm{d}s\,,$$

where the integral is taken along the magnetic line of force connecting the mirror points M and M^*.

In the time-stationary state and in the geomagnetic field, the motion of a charged particle in latitude is then such as to mirror at the same magnetic field B_{m}, and in longitude is such as to conserve I. Consequently, the directional intensity j perpendicular to $\mathbf{B}$ is the same at all points in the geomagnetic field having the same values of B and I. Here j includes particles of all types and energies.

Now the locus of all points having thc same value of I and B is a ring in each hemisphere. The surface described by the magnetic lines of force connecting these rings is called a *magnetic shell.* As discussed by McIlwain (1961), in the geomagnetic field we may take it that two particles which initially mirror at different values of B on the same line of force will drift in longitude essentially on the surface of the same magnetic shell.

Consequently, the omnidirectional intensity J as well as the directional intensity j is the same at all points with the same values of B and I.

As stated by McIlwain (1961): "The fact that all particles that drift through a given line of force will remain on approximately the same shell, leads immediately to the desirability of finding a method of labelling all points – (in the geomagnetic field) – with a number that is unique for each shell."

McIlwain then introduced the parameter L for this purpose with L being only a function of I and B.

L labels a magnetic shell on which a particle bounces from hemisphere to hemisphere in latitude and drifts in longitude. Numerically L is such that, if the geomagnetic field was that of a perfect dipole, then the equatorial radial distance from the center of the earth to a given magnetic shell would be L earth radii.

In the application of the parameter L, tables of I versus B for a model of the actual geomagnetic field must be used. McIlwain (1961) has computed L for the altitude range 500 kilometers to 2000 kilometers using the Jensen and Whitaker (1960) 512-term spherical harmonic expansion of the earth's field and the surface measurements for epoch 1955.0. The estimated accuracy of the values of L is better than about 2 percent. A more general program for calculation of L at any altitude has now been completed (McIlwain, private communication).

The magnetometer measurements with Vanguard III showed that the Jensen and Whitaker expression for the magnetic field was valid to about one percent or better over the altitude range of ~ 510 km to ~ 3750 km in the geographic latitude range 33.4° N to 33.4° S (Heppner *et al.*, 1960).

It was recognized in formulation of the (L, B) system that it would break down above some high magnetic latitude, due to the influence both of the steady solar wind and to magnetic storms. Recently the author has shown (O'Brien, 1962c) that the quasi-steady-state solar wind so distorts the geomagnetic field that L no longer retains its simple applicability even in magnetically-quiet periods for $L \gtrsim 6$. McIlwain suggested that shells with $L \gtrsim 3$ are probably distorted by large magnetic storms. Nevertheless, the (L, B) system of coordinates remains a very useful idealized system or fixed reference system in which the perturbations of the various phenomena as well as the time-stationary unperturbed state may be studied.

The unit of L is an earth radius (6370 kilometers). The unit of B is the Gauss.

It is sometimes useful to refer the L coordinate for a given shell to the latitude at which the shell intersects the surface of the earth. This can be done by using the concept of an invariant latitude ($\Lambda°$) where

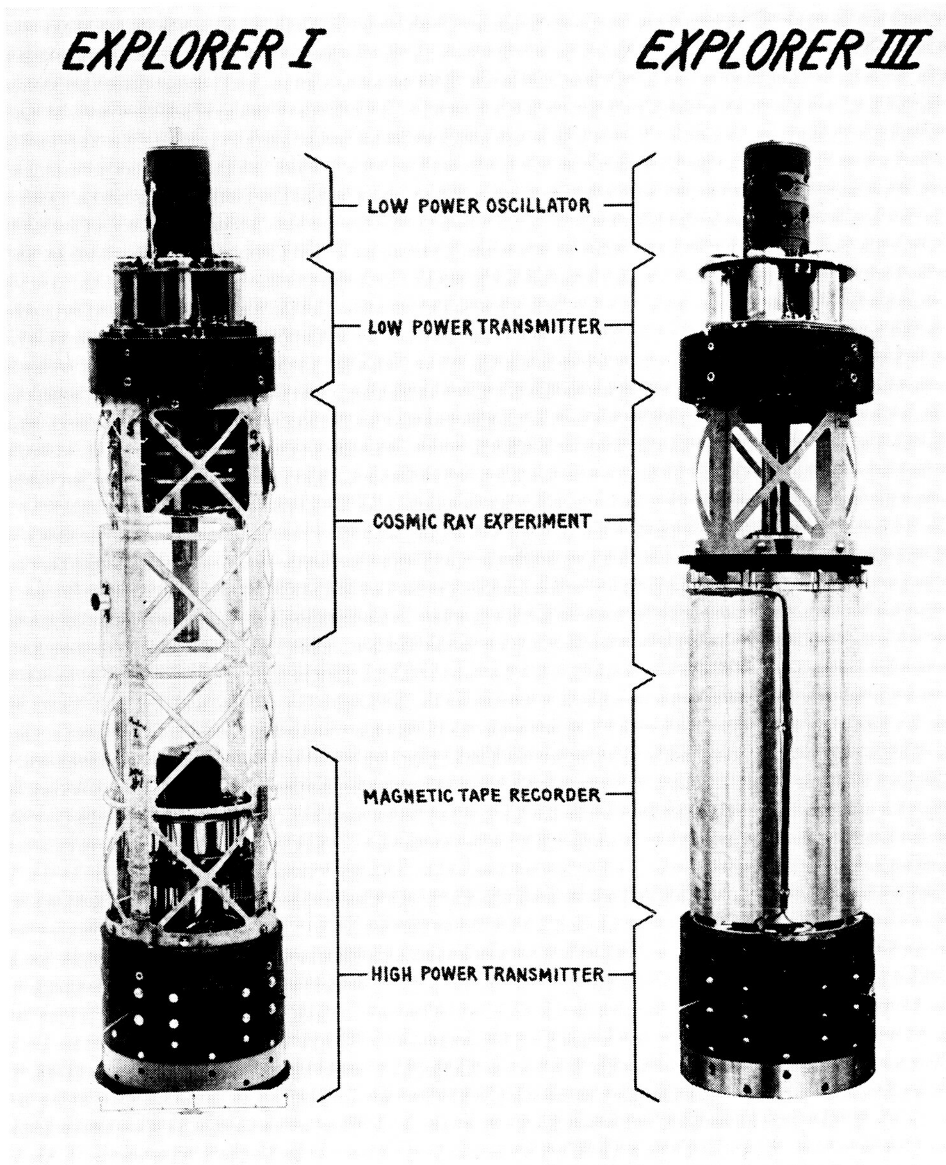
$$L \cos^2 \Lambda° = 1 \, .$$

Over North America, for example, Λ and the centered dipole magnetic latitude (λ) differ at most by 2°. (See also Vestine and Sibley (1960) for combination of ground based auroral observations with I.)

2.3 THE VEHICLE TRAJECTORY OR ORBIT IN (L, B) COORDINATES

Because of the extreme usefulness of the (L, B) system of coordinates, all satellite data treated at the State University of Iowa are routinely referred to the (L, B) system by use of computer programs devised by McIlwain. In the following, all data will be discussed in this coordinate system.

Note that even with a satellite in a circular orbit, the offset of the effective dipole by ~ 400 kilometers from the center of the earth results in a variation of ~ 800 kilometers in the effective magnetic altitude of the satellite at a given latitude over all longitudes. For example, a particle which mirrors at the invariant equator at an altitude of about 1200 kilometers over the mid-Pacific will mirror at an altitude of only about 400 kilometers over the Atlantic (see Vestine and Sibley, 1960).



Explorer I and Explorer III payloads, which differed primarily in that III had an on-board tape recorder for storage of data, while I gave only hot-line data. The single geiger tube on each is apparent in the centre of the column, pointing down on Explorer I and up on III. These large geigers, with effective dimensions 10 cm long and 2 cm diameter, discovered the geomagnetically-trapped radiation by counting so rapidly that they saturated. The instrument package weighed about 11 lbs. (U.S. Army photo).

A satellite in a circular orbit will traverse a mesh of (L, B) points in a few days, but with an eccentric orbit the time required to get a relatively fine coverage of (L, B)

points is a function of the precession of the orbit, its eccentricity, and so on, and it may be many months.

2.4 CHARACTERISTIC TIMES

As discussed by VAN ALLEN (1962), a trapped particle executes three types of angular motion. The first is the simple rotation about **B** with a characteristic time or LARMOR period of order microseconds to milliseconds. The second is the latitudinal oscillation between mirror points, with characteristic "bounce" times of order seconds. The third is the longitudinal drift about the earth, with electrons moving to the east and protons to the west, with characteristic times of order minutes to hours. The actual times are dependent on energy, particle type and **L** etc., and VAN ALLEN (1962) has provided convenient summaries over the range of interest.

3. Historical Review

3.1 GENERAL

Experimental studies of the radiation zones have a dead-time of one year or more. Thus, from the moment of recognizing the need for a measurement and the manner of making it, the experimentalist must spend a year developing an experiment. If he is fortunate, during that same year a satellite of suitable orbital characteristics and technical features will be readied for launching. Since the probability of a successful launch has averaged only about 0.58 in the U.S. (we have no published figures for the USSR attempts), the experimentalist has a high probability of seeing his project destroyed in a spectacular manner. If the launch is successful, and if all the apparatus operates, he must then become involved in the logistical operation of data reduction, which can be very complex and time consuming (see Section 9). Finally, after many more months he may understand his measurements sufficiently well to foresee what experiment should be carried out next, and the cycle begins again. Any malfunctions at launch or in orbit, and the period of the cycle is lengthened.

The existence of the radiation zones has been known for only about four years, and this period can be divided into four cycles. The first cycle was the discovery of the radiation zones by Explorers I and III. The second was the quasi-quantitative examination of the contents of the zones by Explorer IV, Lunik II and rocket-borne apparatus. This second cycle was partly exploratory but was mainly concerned with verifying current speculations about the contents of the zones. The third cycle, overlapping with the second, was largely qualitative study with Pioneer III and IV, Explorer VI and VII, and so on. The fourth and current cycle began with Injun I and Explorer XII, which obtained quantitative information about the studies of the previous cycles, but which also discovered new phenomena which will now have to be measured quantitatively. Furthermore, since the explosion of a nuclear device at high altitude on July 9, 1962 created an intense durable artificial radiation belt, it must be considered that the present (1961–1962) cycle is still largely an exploratory one.

In the following we briefly outline the historical development of present experi-

TABLE 1

Satellite	*Active Life*	*Apogee* Km	*Perigee* Km	*Incli-nation*	*Period*	*Apparatus*
Sputnik I 1957α 2	Oct. 4, 1957 to Oct. 27, 1957	950	227	65°	96 min	Not known
Sputnik II 1957 β	Nov. 3, 1957 to Nov. 9, 1957	1670	225	65°	104 min	2 Geigers
Explorer I 1958 α	Jan. 31, 1958 to March 15, 1958	2500	360	33°	115 min	1 Geiger
Explorer III 1958 γ	March 26, 1958 to May 14, 1958	2800	190	33°	116 min	1 Geiger
Sputnik III 1958 δ 2	May 15, 1958 to June 17, 1958	1880	226	65°	90 min	(a) Scint. (ZnS) (b) Scint. (ZnS) (c) Scint. (NaI) Pulse and D.C. +Magnetometer +Čerenkov ($Z > 15$)
Explorer IV 1958 ε	July 26, 1958 to Sept. 19, 1958	2200	260	51°	110 min	(a) Pulse Scint. (b) D.C. Scint. (c) Geiger Type 302 (d) Geiger type 302
Pioneer I	Oct. 11, 1958 to Oct. 12, 1958	Unsuccessful lunar probe Altitude 60 000 Km				Ionization chamber

DETAILS OF SATELLITES AND SPACE PROBES USED IN RADIATION ZONE STUDIES

Geometric Factors and Shielding		*Detectable Particles*		References S = Scientific T = Technical Only
Directional	*Omnidirectional*	*Directional*	*Omnidirectional*	
	18 cm² ~ 10 g cm⁻²		$E_e \geq$ 20 Mev $E_p \gtrsim$ 100 Mev	(S) VERNOV and CHUDAKOV (1960a) (T) VERNOV *et al.* (1957)
	17.4 cm² ~ 1.5 g cm⁻²		$E_e \gtrsim$ 3 Mev $E_p \gtrsim$ 30 Mev	(S) AONI and KAWAKAMI (1958) (S) VAN ALLEN (1958) (T) LUDWIG (1959) (T) RICHTER *et al.* (1959)
	17.4 cm² ~ 1.5 g cm⁻²		$E_e \gtrsim$ 3 Mev $E_p \gtrsim$ 30 Mev	(S) VAN ALLEN *et al.* (1958)
5 cm² sterad 0.4 mg cm⁻² Al 5 cm² sterad 0.8 mg cm⁻² Al	2 mg cm⁻² thick and 5 cm diameter under 1.3 g cm⁻² of Al 3.9 cm thick and 4 cm diameter under 1 g cm⁻² Al	$E_e \gtrsim$ 15 kev $E_p \gtrsim$ 200 kev $E_e \gtrsim$ 25 kev $E_p \gtrsim$ 400 kev	$\Delta E \gtrsim$ 35 kev and $\int \Delta E \, dt$	(S) KRASOVSKII *et al.* (1961) (S) BASLER *et al.* (1960) (S) VERNOV *et al.* (1961)
0.040 cm² sterad 0.14 g cm⁻² Al 0.024 cm² sterad 1 mg cm⁻² Ni + Al	0.33 cm² $\gtrsim$ 5 g cm⁻² 0.35 cm² $\geqslant$ 5 g cm⁻² $\geqslant$ 0.14 cm² 1.2 g cm⁻² steel minimum $\lesssim$ 0.14 cm² 1.2 g cm⁻² steel + 1.6 g cm⁻² Pb minimum	$E_e \gtrsim$ 600 kev E_p 9.5 $\geqslant$ Mev $E_e \geqslant$ 20 kev $E_p \gtrsim$ 400 kev	$E_e \gtrsim$ 3 Mev $E_p \gtrsim$ 31 Mev $E_e \gtrsim$ 5 Mev $E_e \gtrsim$ 40 Mev	(S) VAN ALLEN *et al.* (1959 a and b) (S) ROTHWELL and MCILWAIN (1960) (T) MC ILWAIN (1961) (T) LUNDQUIST *et al.* (1961)
	12 cm² Min. 0.45 g cm⁻²		0.5 to 10⁶ röntgen/hour	(S) ROSEN *et al.* (1959)

TABLE 1 *(continued)*

Satellite		*Active Life*	*Apogee* Km	*Perigee* Km	*Incli-nation*	*Period*	*Apparatus*
Pioneer III		Dec. 6, 1958 to Dec. 7, 1958	Unsuccessful space probe Altitude 109.000 Km Re-entered				(a) Geiger type 302 (b) Geiger type 213
Lunik I	Artificial Planet 1	Jan. 2, 1959	In orbit around sun				(a) 2 Geigers (b) Scint. (NaI) 3 Pulse levels + d.c. (c) D.C. Scint.
Pioneer IV	Artificial Planet 2	March 3, 1959 to March 6, 1959	In orbit around sun				(a) Geiger type 302 (b) Geiger type 213
Explorer VI	1959 δ 1	Aug. 7, 1959 to Oct. 6, 1959	42.000	230	50°	12-3/4 hours	(1a) Geiger type 302 (1b) Ion. Chamber (2a) Pulse Scint. $\Delta E \gtrsim 100$ kev (3a) 7 Semiprop. counters + Magneto-meter
Lunik II							(a) Scint. (NaI) 3 Pulse levels + D.C.

Geometric Factors and Shielding		*Detectable Particles*		*References* S = Scientific T = Technical Only
Directional	*Omnidirectional*	*Directional*	*Omnidirectional*	
	0.75 cm^2 Min. 0.67 g cm^{-2}		$E_e \gtrsim$ 2.2 Mev $E_p \gtrsim$ 30 Mev	(S) VAN ALLEN and FRANK (1959a)
	$\sim$ 0.09 cm^2			
	Same as (a)		Same as (a)	
	$\sim$ 5 cm^2 and $\sim$ 18 cm^2 and 1 g cm^{-2} Al		$E_e \gtrsim$ 2 Mev $E_p \gtrsim$ 30 Mev	
	19 cm^2		$E_e \gtrsim$ 200 kev $E_p \gtrsim$ 30 Mev	(S) VERNOV and CHUDAKOV (1960 a, b)
	and 1 g cm^{-2} Al		$\Delta E \gtrsim$ 45 kev $\Delta E \gtrsim$ 450 kev $\Delta E \gtrsim$ 4500 kev	(S) VERNOV *et al.* (1959)
0.3 g cm^{-2} thick crystal 1.9 mg cm^{-2} Al over 1.8 sterad		$E_e \gtrsim$ 50 kev $E_p \gtrsim$ 700 kev		
	$\sim$ 0.75 cm^2 Min. 0.67 g cm^2		$E_e \gtrsim$ 2.2 Mev $E_p \gtrsim$ 30 Mev	(S) VAN ALLEN and FRANK (1959 b)
	$\sim$ 0.09 cm As for (a) + 4 g cm^{-2} Pb + 0.6 g cm^{-2} steel		$E_e \gtrsim$ 8 Mev $E_p \gtrsim$ 50 Mev	
	0.55 to 0.75 cm^2 $\sim$ 1 g cm^{-2}		$E_e \gtrsim$ 2 Mev $E_p \gtrsim$ 16 Mev	(S) ARNOLDY *et al.* (1960, 1962)
	45 cm^2 $\sim$ 1 g cm^{-2}		As in (1a)	HOFFMAN *et al.* (1962)
2 × 10^{-4} cm^2 3.3 mg cm^{-2}	See Ref.	$E_e \gtrsim$ 220 kev $E_p \gtrsim$ 2 Mev	$E_e \gtrsim$ 500 kev $E_p \gtrsim$ 10 Mev	(S) ROSEN *et al.* (1960) ROSEN and FARLEY(1961) ARNOLDY *et al.* (1962)
	Coincidence and singles		$E_e \gtrsim$ 13 Mev	(S) FAN *et al.* (1960a) ARNOLDY *et al.* (1962)
	$\sim$ 5 g cm^{-2} Pb		$E_p \gtrsim$ 70 Mev Also *bremss.* only	SIMPSON *et al.* (1962) FAN *et al.* (1961)
	$\sim$ 16 cm^2 1 g cm^{-2} Al		$E_e \gtrsim$ 2 Mev $E_p \gtrsim$ 30 Mev $\Delta E \gtrsim$ 60 kev $\Delta E \gtrsim$ 600 kev $\Delta E \gtrsim$ 3.5 Mev	(S) VERNOV and CHUDAKOV (1960 b)

TABLE 1 (continued)

Satellite		Active Life		Apogee Km	Perigee Km	Incli- nation	Period	Apparatus
Lunik II	Lunar Probe	Sept. 12, to Sept. 13,	1959 1959	Impacted on moon				(b) Geiger (c) Geiger (d) Scint. (NaI) 2 Pulse levels + D.C. (e) Scint. (CsI) D.C. (f) Geiger (g) Geiger (h) Geiger (i) Ion trap + Čerenkov array
Lunik III	1959 θ	Oct. 4, to Oct. 18,	1959 1959	470 000	40 000	77°	16 days	None reported
Explorer VII	1959 *i* 1	Oct. 13, to Feb.,	1959 1961	1090	555	50°	101 min	(a) Geiger type 302 (b) Geiger type 112
Pioneer V	1960 α	March 11, to June 26,	1960 1960	In solar orbit				(1a) Geiger type 302 (1b) Ion Chamber (2) 7 Semiprop. counters
Sputnik V								(a) Geiger

Geometric Factors and Shielding		*Detectable Particles*		*References* S = Scientific T = Technical Only
Directional	*Omnidirectional*	*Directional*	*Omnidirectional*	
	$\sim$ 5 cm^2 1 g cm^{-2} Al + 1.4 g cm^{-2} Cu		$E_e \gtrsim$ 5 Mev $E_p \gtrsim$ 45 Mev	
	$\sim$ 5 cm^2 1 g cm^{-2} Al + 3.4 g cm^{-2} Pb		$E_e \gtrsim$ 8 Mev $E_p \gtrsim$ 50 Mev	
	$\sim$ 16 cm^1 1 g cm^{-2} Al		$E_e \gtrsim$ 2 Mev $E_p \gtrsim$ 30 Mev $\Delta E \gtrsim$ 45 kev $\Delta E \gtrsim$ 450 kev	
3 cm^2 $\times$ 0.3 cm 1.2 mg cm^{-2} Al		$E_e \gtrsim$ 40 kev $E_p \gtrsim$ 500 kev		
Window 0.28 cm^2 with 0.05 g cm^{-2} Pb	+ 3.4 g cm^{-2} Pb	$E_e \gtrsim$ 250 kev $E_p \gtrsim$ 5 Mev		
Window 1.6 cm^2 As in (f) + 0.18 g cm^{-2} Cu	+ 3.4 g cm^{-2} Pb	$E_e \gtrsim$ 600 kev $E_p \gtrsim$ 10 Mev		
Window 1.6 cm^2 As in (f) + 0.45 g cm^{-2} Cu	+ 3.4 g cm^{-2} Pb	$E_e \gtrsim$ 1 Mev $E_p \gtrsim$ 20 Mev		
See Ref.	See Ref.	$E_e \gtrsim$ 200 ev		(S) GRINGAUZ *et al.* (1961a, b) (T) GRINGAUZ *et al.* (1962)
	0.61 cm^2 $\sim$ 0.6 g cm^{-2}		$E_e \gtrsim$ 1.1 Mev $E_p \gtrsim$ 18 Mev	(S) VAN ALLEN and LIN (1960) (S) O'BRIEN *et al.* (1960)
	9.0 cm^2 $\sim$ 0.5 g cm^{-2} + 1.1 g cm^{-2} Pb		$E_e \gtrsim$ 2.5 Mev $E_p \gtrsim$ 30 Mev	(S) PIZZELLA *et al.* (1962a) (S) FORBUSH *et al.* (1961, 1962) (T) LUDWIG and WHELPLEY (1960)
	Same as (1a) on Explorer VI			(S) ARNOLDY *et al.* (1960c)
	Same as (1b) on Explorer VI			
	Same as (3a) on Explorer VI			(S) FAN *et al.* (1960b)
	$\gtrsim$ 5 g cm^{-2}		$E_e \gtrsim$ 8 Mev $E_p \gtrsim$ 60 Mev	(S) VERNOV *et al.* (1962)

TABLE 1 *(continued)*

Satellite		*Active Life*	*Apogee* Km	*Perigee* Km	*Incli-nation*	*Period*	*Apparatus*
Sputnik V (2nd space vehicle)	1960 λ 1	Aug. 19, 1960 to Aug. 20, 1960	300	300	65°	91 min	(b) Scint. (NaI) Pulse and D.C. (c) Scint. (CsI) D.C. (d) Geiger telescope
Discoverer XVII	1960 ο	Nov. 12, 1960 to Nov. 14, 1960	990	180	82°	96 min	Nuclear emulsions recovered
Sputnik VI (3rd space vehicle)	1960 ρ 1	Dec. 1, 1960 to Dec. 2, 1960	270	190	65°	89 min	(a) Geiger (b) Scint. (NaI) Pulse and D.C.
Sputnik VI	1960 ρ 1	Dec. 1, 1960 to Dec. 2, 1960	270	190	65°	89 min	(c) Geiger telescope
Discoverer XVIII	1960 σ	Dec. 7, 1960 to Dec. 10, 1960	680	230	81°	94 min	Nuclear emulsions recovered
Sputnik VII	1961 β 1	Feb. 4, 1961 to Feb. 26, 1961	330	220	65°	90 min	Not known
Venus Probe	1961 γ 1	Feb. 12, 1961	In solar orbit				Geigers and scintillation counters
Explorer XI	1961 ν	April 27, 1961	1790	490	29°	108 min	(a) Plastic scint. (two sections) (b) "Sandwich" scint. (NaI + CsI) (c) Čerenkov) (Pulse height discrimination)
Injun I							(a) Geiger

Geometric Factors and Shielding		*Detectable Particles*		*References* S = Scientific T = Technical Only
Directional	*Omnidirectional*	*Directional*	*Omnidirectional*	
	3 cm × 1.4 cm $\gtrsim$ 5 g cm^{-2}		$E_e \gtrsim$ 8 Mev $E_p \gtrsim$ 60 Mev and $\Delta E \gtrsim$ 25 kev	(S) VERNOV *et al*, (1962)
13 cm^2 sterad 0.002 g cm^{-2} Al 2.5 cm^2 sterad with 5 g cm^{-2} between counters		$E_e \gtrsim$ 30 kev $E_p \gtrsim$ 1 Mev $E_e \gtrsim$ 8 Mev $E_p \gtrsim$ 60 Mev		(S) SAVENKO *et al.* (1961) (S) GINZBURG *et al.* (1962)
	2.2 g cm^{-2} minimum			(S) YAGODA (1961)
"Slightly different from those in Sputnik V"				(S) VERNOV *et al.* (1962)
2.5 cm^2 sterad with 5 g cm^{-2} between counters		$E_e \gtrsim$ 8 Mev $E_p \gtrsim$ 60 Mev		(S) GINZBURG *et al.* (1962)
	2.2 g cm^{-2} minimum			(S) YAGODA (1961)
Not known				(S) VERNOV *et al.* (1962) (S) GRINGAUZ (1961a)
0.028 g cm^{-2} Al	1.4 g cm^{-2} Al	$E_e \gtrsim$ 350 kev $E_p \gtrsim$ 3.5 Mev	$E_e \gtrsim$ 1 Mev $E_p \gtrsim$ 35 Mev	(S) GARMIRE (1962)
Not used in initial analysis (See ref.)				
See ref.		$E_e \gtrsim$ 15 Mev $E_p \gtrsim$ 350 Mev		
1.2 mg cm^{-2} mica 1.5 × 10^{-2} cm^2 sterad	4.5 g cm^{-2} Pb ~ 0.2 cm^2	$E_p \gtrsim$ 40 kev $E_p \gtrsim$ 500 kev	$E_e \gtrsim$ 8 Mev $E_p \gtrsim$ 60 Mev	(S) O'BRIEN *et al.* (1962b)

TABLE 1 *(continued)*

Satellite		*Active Life*	*Apogee* Km	*Perigee* Km	*Incli-nation*	*Period*	*Apparatus*
Injun I	1961 o 2	June 29, 1961 to present	1020	860	67°	104 min	(b) Magnetic spectrometer (c) 2 CdS Total-Energy Detectors (d) 2 as in (c) plus magnets (e) 4 p–n junction detectors + Aspect and magnetometer
Midas 3	1961 σ 1	July 12, 1961 to Sept 11, 1961	3500	3400	91°	160 min	(a) Scint. (Plastic) Pulse (b) Same as (a) (c) Geiger type 302 + Čerenkov
Explorer XII	1961 ε	Aug. 16, 1961 to Dec. 6, 1961	77,000	300	34°	26–1/2 hours	(1a) Geiger type 302 (1b) Magnetic Spectrometer (1c) CdS Total-Energy Detector (1d) As in (1c) plus magnet (2a) Scint. (ZnS) Pulse and D.C. + Magnetometer + Aspect
Discoverer XXIX							(1) Magnetic Spectrometer

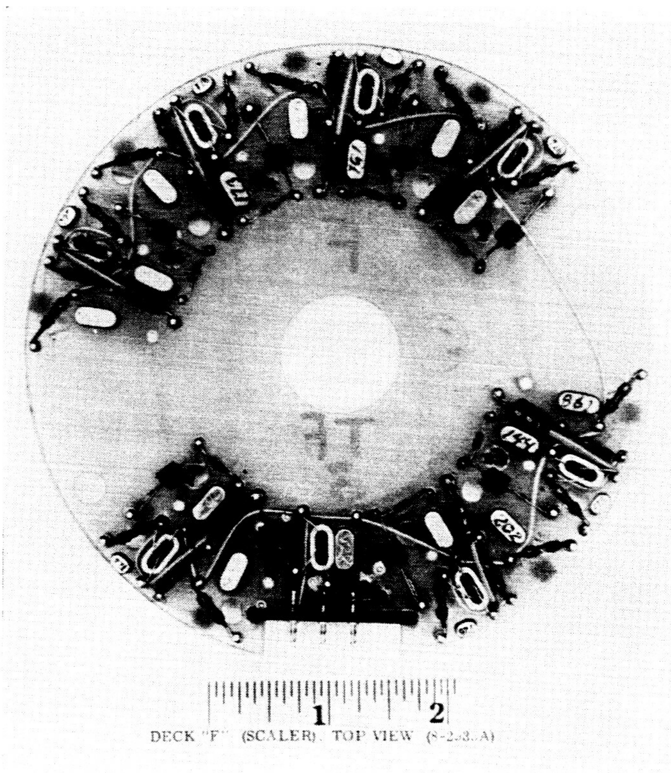
Geometric Factors and Shielding		*Detectable Particles*		*References* S = Scientific T = Technical Only
Directional	*Omnidirectional*	*Directional*	*Omnidirectional*	
1.2 mg cm^{-2} mica $\sim 5 \times 10^{-5}$ cm^2 sterad	$\gtrsim$ 3.5 g cm^{-2} Pb $\sim$ 0.1 cm^2	40 kev $\lesssim$ $E_e \lesssim$ 60 kev 80 kev $\lesssim$ $E \lesssim$ 110 kev	$E_e \gtrsim$ 6 Mev $E_p \gtrsim$ 50 Mev	(T) O'Brien and Whelpley (1962)
Zero shielding 3×10^{-4} cm^2 sterad Zero shielding 3×10^{-4} cm^2 sterad		$E_e \gtrsim$ 1 kev $E_p \gtrsim$ 5 kev $E_e \gtrsim$ 250 kev $E_p \gtrsim$ 5 kev		(S) Freeman (1962)
2.6 mg cm^{-2} 2.8×10^{-2} cm^2 sterad	$\gtrsim$ 3.5 g cm^{-2} Al	1.5 Mev $\lesssim$ $E_p \lesssim$ 15 Mev	$E_e \gtrsim$ 7 Mev $E_p \gtrsim$ 60 Mev	(S) Pieper *et al.* (1962)
	6 g cm^{-2} W 3.6 cm^2 22 g cm^{-2} W 3.6 cm^2 $\sim$ 5 g cm^{-2} Brass $\sim$ 0.5 cm^2		$E_e \gtrsim$ 20 Mev $E_p \gtrsim$ 87 Mev $E_e \gtrsim$ 40 Mev $E_p \gtrsim$ 148 Mev $E_e \gtrsim$ 10 Mev $E_p \gtrsim$ 60 Mev	(S) Smith *et al.* (1962)
1.2 mg cm^{-2} $\sim 5 \times 10^{-5}$ cm^2 sterad Zero shielding 3×10^{-4} cm^2 sterad Zero shielding 3×10^{-4} cm^2 sterad	$\sim$ 0.7 g cm^{-2} 0.75 cm^2 $>$ 3.5 g cm^{-2} Pb 0.2 cm^2	40 kev $\lesssim E_e$ $\lesssim$ 60 kev 80 kev $\lesssim E_e$ $\lesssim$ 110 kev $E_e \gtrsim$ 1 kev $E_p \gtrsim$ 5 kev $E_e \gtrsim$ 250 kev $E_p \gtrsim$ 5 kev	$E_e \gtrsim$ 1.6 Mev $E_p \gtrsim$ 20 Mev $E_e \gtrsim$ 6 Mev $E_p \gtrsim$ 50 Mev	(S) O'Brien *et al.* (1962a)
Variable See ref.		10 kev $\lesssim E_e$ $\lesssim$ 100 kev 100 kev $\lesssim E_p$ $\lesssim$ 4.5 Mev		(S) Davis and Williamson (1962)
				(S) Cahill and Amazeen (1962)
$\sim 5 \times 10^{-3}$ cm^2 sterad		10 channels 80 kev $\leqslant E_e$ $\leqslant$ 1.2 Mev		(S) West *et al.* (1962) (S) Mann *et al.* (1962)

TABLE 1 *(continued)*

Satellite		*Active Life*	*Apogee Km*	*Perigee Km*	*Inclination*	*Period*	*Apparatus*
Discoverer XXIX	1961 ψ	Aug. 30, 1961 to Sept. 4, 1961	550	220	82°	91 min	(2a) Scint. (CsI) Pulse (2b) Scint. (Plastic) Pulse
Discoverer XXXI	1961 $\alpha\beta$	Sept. 17, 1961 to Sept 22, 1961	410	240	83°	91 min	As in Discoverer XXIX
Midas 4	1961 $\alpha\delta$	Oct. 13, 1961 to Oct. 31, 1961	3700	3500	95°	172 min	(1a) Scint. (Plastic) Pulse (1b) Scint. (Plastic) Pulse (1c) As in (1a) (1d) As in (1a) (1e) As in (1a) (1f) As in (1a) (1g) Geiger type 302 (1h) As in (g) (1i) As in (g) (1j) As in (g)
Discoverer XXXIV	1961 $\alpha\varepsilon 1$	Nov. 5, 1961	1030	220	83°	97 min	Same as (2a) and (2b) in Discoverer XXIX
TRAAC	1961 $\alpha\eta 2$	Nov. 15, 1961 to Aug. 14, 1962	1160	900	32°	106 min	(1a) 4 p–n junctions (1b) 2 p–n junctions (2a) Geiger type 213 (2b) Geiger type 302 (1c) Neutron p–n junction detectors
Discoverer XXXVI	1961 $\alpha\kappa 1$	Dec. 12, 1961	450	240	81°	92 min	Same as (2a) and (2b) in Discoverer XXIX

Geometric Factors and Shielding		*Detectable Particles*		*References* S = Scientific T = Technical Only
Directional	*Omnidirectional*	*Directional*	*Omnidirectional*	
9 mg cm^{-2} Be ~ 15 cm^2 sterad	~ .2 g cm^{-2} Al ~ 60 cm^2	$E_e \gtrsim$ 100 kev $E_p \gtrsim$ 3 Mev	$E_e \gtrsim$ 2 Mev $E_p \gtrsim$ 15 Mev	(S) SEWARD *et al.* (1962)
	1.6 g cm^{-2} Al 1.5 cm^2 ~ 9 g cm^{-2} W 2.1 cm^2 ~ 22 g cm^{-2} W 2.7 cm^2 .1 g cm^{-2} Al 1.1 cm^2 ~ 9 g cm^{-2} W 1.7 cm^2 ~ 22 g cm^{-2} W 2.6 cm^2 ~ 2 g cm^{-2} ~ 0.5 cm^2 5 g cm^{-2} ~ 0.5 cm^2 ~ 1 g cm^{-2} ~ 0.5 cm^2 5 g cm^{-2} ~ 0.5 cm^2		$E_p \gtrsim$ 59 Mev $E_p \gtrsim$ 95 Mev $E_p \gtrsim$ 148 Mev $E_p \gtrsim$ 34 Mev $E_p \gtrsim$ 87 Mev $E_p \gtrsim$ 144 Mev $E_p \gtrsim$ 46 Mev $E_p \gtrsim$ 76 Mev $E_e \gtrsim$ 2 Mev $E_p \gtrsim$ 25 Mev $E_p \gtrsim$ 75 Mev	(S) SMITH *et al.* (1961) Note: Threshholds for electrons not shown since shielding so heavy.
2.6 mg cm^{-2} Al 18.5 mg cm^{-2} Al 170 mg cm^{-2} Al and 0.07 cm^2 sterad 2.6 mg cm^{-2} Al 0.07 cm^2 sterad 1.2 mg cm^{-2} 5 × 10^{-2} cm^2 sterad	~ 0.7 g cm^{-2} ~ 0.75 cm^2	1.1 Mev $\lesssim E_p \lesssim$ 39 Mev 3 Mev $\lesssim E_p \lesssim$ 34 Mev 10 Mev $\lesssim E_p \lesssim$ 34 Mev 4 Mev $\lesssim E\alpha \lesssim$ 20 Mev $E_e \lesssim$ 40 kev $E_p \gtrsim$ 500 kev	$E_e \gtrsim$ 1.6 Mev $E_p \gtrsim$ 23 Mev	(T) BOSTROM *et al.* (1962)
See ref.		~ ev $\lesssim E_n \lesssim$ 2 Mev		(T) WILLIAMS *et al.* (1962)

mental knowledge of the radiation zones. Since much of the development came about through undocumented verbal communications between scientists rather than through publications, the treatment below is quite incomplete. Only experiments reported in the literature from vehicles launched before January, 1962, will be discussed.



Explorer III time-base scaler, with seven stages of binary scaling. Dimensions in inches. (see LUDWIG, 1959).

Pertinent experiments of spacecraft successfully launched are listed in Table 1, together with details of the reported period over which were data obtained, the orbital characteristics, the particle types and energies studied, and so on. Where these are available, both a scientific and a technical reference are given for each experiment. The symbols E_e, E_p, etc. are used to represent the energy of an electron, the energy of a proton, and so on. The geometric factor of a detector is the number which is divided into the counting rate of the detector to give the particle flux.

A very great deal of the more definitive information about the radiation zones has been obtained with relatively low altitude ($\sim$ 1000 kilometer) rockets, and relevant experiments carried out with them are listed in Table 2.

Experiments on vehicles launched unsuccessfully are not included in either table. There are clearly various degrees of lack of success in a launching, and we have rather arbitrarily included Pioneer I and Pioneer III in Table 1, but have not included Ranger I and Ranger II which had extensive scientific payloads and were put into "parking" orbits at low altitudes instead of the planned $\sim 10^6$–km high orbits. It is likely that detectors on these Rangers will give useful information (VAN ALLEN, private communication) but none is published to date. Several of the unsuccessful payloads have been documented extensively, and indeed the review of the S-46 payload built by the State University of Iowa and launched unsuccessfully on March 23, 1960, is a very extensive and informative study of the development of a payload for investigation of the radiation zones (LUDWIG, 1960). With unsuccessful experiments, the absence of flight data often leads to better documentation than with successful experiments.

One of the main difficulties in reading early studies of the radiation zones and in trying to interpret them in the light of present knowledge is the absence of the systematic use of a coordinate system (such as the L, B system) in which temporal changes of the radiation can be reliably distinguished from spatial effects. Wherever possible in the following, both new and old measurements are discussed in terms of L and B.

3.2 DISCOVERY OF THE RADIATION ZONES

The early satellite experiments were designed to study cosmic rays above the earth's atmosphere and in a region where shadowing by the earth was reduced, and to study auroral and solar corpuscular radiation in a similar environment (VAN ALLEN, 1956; BARDIN, 1958). There was no explicit prediction of radiation zones, although the theoretical groundwork for their existence was well known (STÖRMER, 1955).

The first report of the existence of geomagnetically-trapped radiation was based on the anomalously *low* counting rates of shielded geiger tubes in Explorers I and III when they reached altitudes of more than ~ 1000 kilometers. The effect was correctly interpreted as being due to saturation of the geiger tube circuitry by high fluxes of particles, and because the radiation was confined to high altitudes, it was concluded that it was geomagnetically confined, and hence that it consisted of charged particles (VAN ALLEN, 1958; VAN ALLEN *et al.*, 1958). Contrary to the first report (VAN ALLEN, 1958) it appears very likely that the dominant contribution to the geiger rates on Explorers I and III was from penetrating protons in the studies reported to date (VAN ALLEN *et al.*, 1958; YOSHIDA, LUDWIG, and VAN ALLEN, (1960), where L values have been less than about 2.0.

The geiger tubes on Sputnik II showed enhanced counting rates at geographic latitudes above 60° N and altitudes between 225 and 700 kilometers over U.S.S.R. territory (VERNOV *et al.*, 1958). The corresponding L values are between 3 and 4, and it appears most likely that the heavily shielded geigers detected *Bremsstrahlung* from electrons.

3.3 EXPLORATION OF THE SPATIAL DISTRIBUTION

The apparatus on the next Soviet satellite (Sputnik III) and the next U.S. satellite (Explorer IV) included scintillation counters which gave more definitive information

TABLE 2

ROCKET-BORNE STUDIES OF THE RADIATION ZONES

Date	*Max. Alt.* (km)	L	*Apparatus*	*Detectable Particles*	*Reference*
1953–1955	~ 100	~ 3 to ~ 30	Geigers and pulse scint.	See Ref.	VAN ALLEN (1961)
Feb. 22 and Feb. 25, 1958	~ 120	~ 8	Proton and electron Spectrometers, geiger	$3\ \text{keV} \leq E_e \leq 100\ \text{keV}$ $25\ \text{keV} \leq E_p \leq 2.5\ \text{MeV}$	MCILWAN (1960a)
Aug. 1 to Sept. 2, 1958 (13 successful)	~ 800	See ref.	8 Shielded geigers (Argus studies)	$170\ \text{keV} \leq E_e$ to $\gtrsim 4\ \text{MeV}$ $4\ \text{MeV} \leq E_p$ to $\gtrsim 40\ \text{MeV}$	ALLEN *et al.* (1959)
Jan. 26, March 16, March 22 and Nov. 16, 1958	~ 180	~ 8	Proton and electron spectrometers, geiger	$30\ \text{ev} \leq E_e \leq 100\ \text{keV}$ $50\ \text{keV} \leq E_p \leq 1.5\ \text{MeV}$	DAVIS *et al.* (1961)
Feb. 2, 1959 July 21, 1959 Aug. 24, 1959	900 1176 1500	(Range (~ 1.35) (see ref.)	Sets of eight geigers with shielding and magnets	$30\ \text{keV} \leq E_e \lesssim 6\ \text{MeV}$	HOLLY *et al.* (1961)
July 21, 1959	1176	~ 1.35	Nuclear emulsions	$E_p \gtrsim 40\ \text{MeV}$	YAGODA (1960)
April 7, 1959	1230	Range	Nuclear emulsions	$E_p \geq 75\ \text{MeV}$	FREDEN and WHITE (1959)
May 21, 1959	same	same	Nuclear emulsions	$E_p \geq 58\ \text{MeV}$	FREDEN and WHITE (1960)
July 7, 1959	1045	~ 2.4	Magnetic spectrometer and geiger	$50\ \text{keV} \leq E_e \leq 1.5\ \text{MeV}$ $E_p \gtrsim 1\ \text{MeV}$	CLADIS *et al.* (1961)
July 21, 1959	1176	~ 1.35	Nuclear Emulsions	$E_e \geq 4\ \text{MeV}$ $E_p \geq 42\ \text{MeV}$	ARMSTRONG *et al.* (1961) same as HOLLY and YAGODA above
Jan. 6, 1960	~ 1400	~ 1.5	B^{10} F_3 counter	$E_n \gtrsim 25\ \text{keV}$	HESS and STARNES (1960)
May, 1960	~ 2000	Range	Scintillators	$E_e \gtrsim 50\ \text{keV}$ $E_p \gtrsim 600\ \text{keV}$	KNECHT (1962)
July 1, 1960	1400	2.7	Geiger	$E_e \gtrsim 4\ \text{MeV}$ $E_p \gtrsim 48\ \text{MeV}$	GURTLER (1961)
Sept. 19, 1960	1880	$1.47 \leq L \leq 1.79$	Nuclear emulsions with time resolution	$E_p \gtrsim 15\ \text{MeV}$	NAUGLE and KNIFFEN (1962)
Oct. 4, 1960	5542	~ 2.5	Scintillator spectrometer and geiger	$1\ \text{MeV} \leq E_p \lesssim 80\ \text{MeV}$	BAME *et al.* (1961)
Oct. 13, 1960	1185	~ 1.35	Nuclear emulsions	$E_p \gtrsim 12\ \text{MeV}$	HECKMAN and ARMSTRONG (1962)
Oct. 13, 1960	same flight		Nuclear emulsions	$E_p \geq 15\ \text{MeV}$	FREDEN and WHITE (1962)
Oct. 28, 1960	145	~ 8	Geigers and Scint.	$E_e \gtrsim 30\ \text{keV}$ $E_p \gtrsim 500\ \text{keV}$	MCDIARMID *et al.* (1961)
Dec., 1961			Geigers and Scint. spectrometer	$80\ \text{keV} \leq E_e \leq 650\ \text{keV}$ $28\ \text{MeV} \leq E_p \leq 200\ \text{MeV}$	IMHOF *et al.* (1962)

about the trapped radiation. Much of the design of the Explorer IV instrumentation was based on plans to study with it the products of the Argus series of high altitude nuclear explosions. Both satellites found regions of enhanced counting rates at high latitudes ($L \approx 3$ to 4) and low latitudes ($L \approx 1.5$), with a region of low counting rate between ($L \approx 2$). (VERNOV and CHUDAKOV, 1960; VAN ALLEN, MCILWAIN, and LUDWIG, 1959).

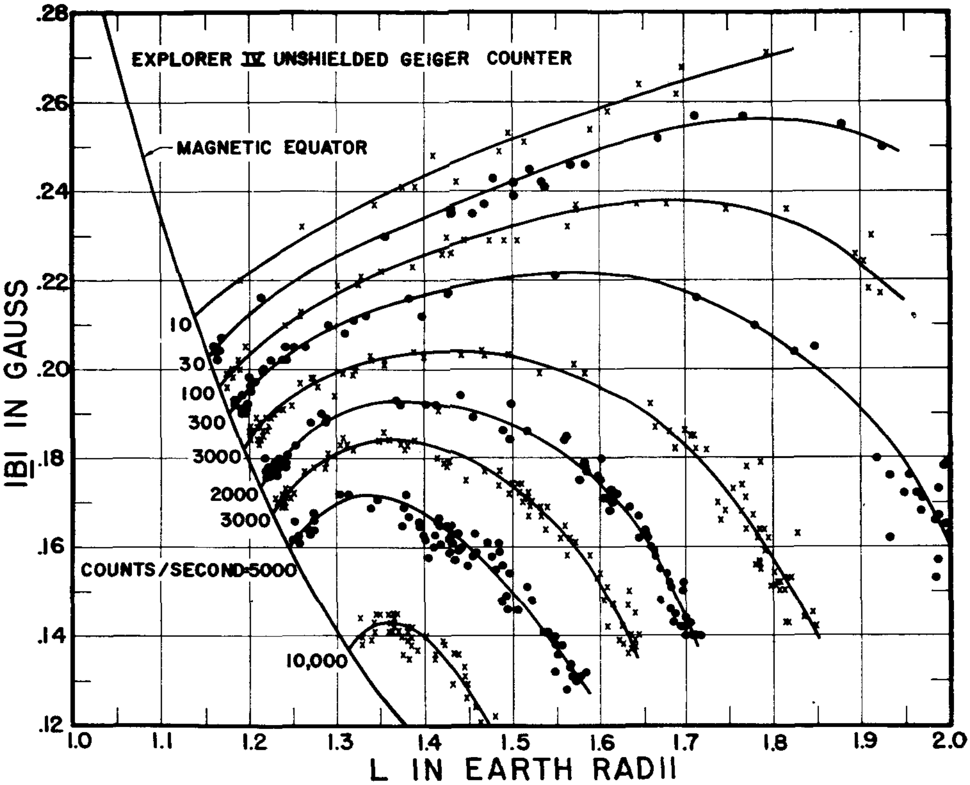


Fig. 1. Counting rates of the unshielded geiger tube on Explorer IV. For interpretation, see text (courtesy of C. MCILWAIN).

When the space probe Pioneer III found that this distinction into two regions of high counting rate was present in the equatorial plane also, the two regions were called the inner and the outer radiation zones, and the intermediate region of lower counting rate was called the "slot" (VAN ALLEN and FRANK, 1959a). In this review we refer to the region $L \leqslant 2$ as the inner zone, and the region $L > 2$ as the outer zone. As we will see, this separation into two zones was a more-or-less fortuitous consequence of the fact that the early studies of the spatial extent were carried out with shielded geiger tubes, which detected penetrating particles most efficiently (see Table 1).

The spatial distribution of the radiation zones was mapped out initially by shielded geiger tubes. The distribution of counting rates of the two geiger counters of Explorer IV for $L \lesssim 2$ are shown in Figures 1 and 2 (McIlwain, 1961), and for a geiger counter in Explorer VII in Figure 3.

Comparison of Pioneer III and Pioneer IV geiger counting rates showed little change in the inner zone, but a very great change in the outer zone, where the peak counting rate and the radial extent of high counting rate were both much greater in Pioneer IV than in Pioneer III. The contrast in temporal variations in the zones was

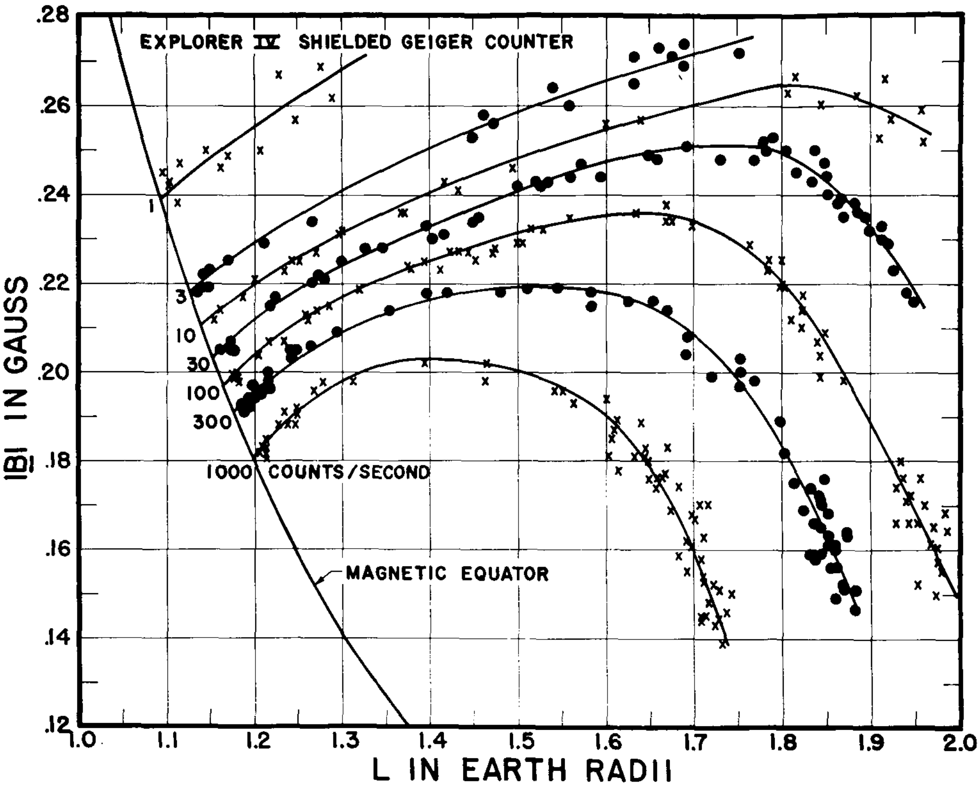


Fig. 2. Counting rates of the shielded geiger tube in Explorer IV. For interpretation, see text (courtesy of C. McIlwain).

commonly thought to be due to their different origins (see for example Van Allen, 1959). Many of the studies of 1959 and 1960 were of the variations in the counting rates of geiger tubes in the outer zone and correlation of these changes with magnetic storms (e.g. Rothwell and McIlwain, 1960, with Explorer IV; Arnoldy *et al.*, 1960, with Explorer VI; Van Allen and Lin, 1960; O'Brien *et al.*, 1960; Forbush *et al.*, 1961, with Explorer VII). Subsequent investigations have established that the flux and energy of the particles which caused these varying counting rates are generally indeterminate (see Section 3.4 and Section 7). By observations for about one year with Explorer VII, Pizzella *et al.* (1962a) found that significant temporal variations did occur in the inner zone. Crudely speaking, for the range $L = 1$ to $L \approx 2.5$, at times of large magnetic storms, the proportional change in counting rate of a shielded geiger tube in Explorer VII increased as L increased.

The directional detectors on Explorer IV (which rotated rapidly) showed that the angular distribution of the natural radiation was disc-like, as expected. The directional detectors on Sputnik III (which rotated very slowly) found that the most intense fluxes were generally at $\alpha = 90°$, but on one occasion they also found an intense flux of

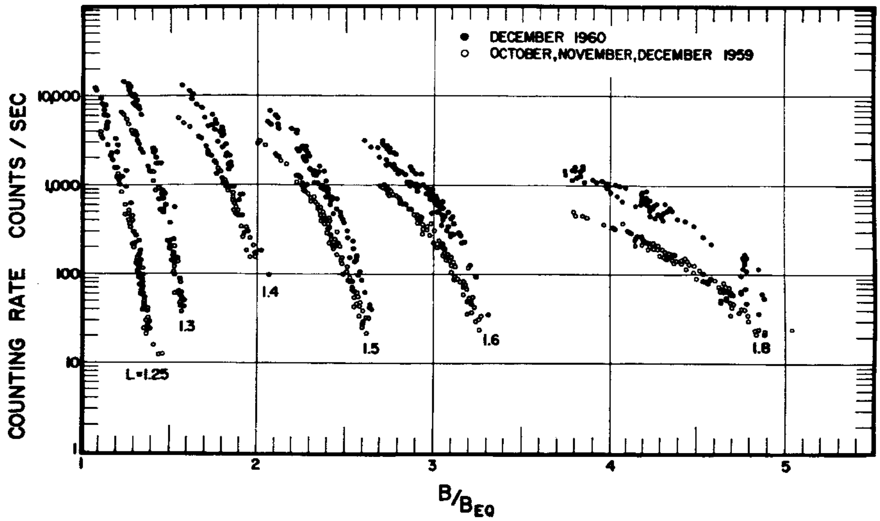


Fig. 3. Counting rate of the type 302 geiger tube in Explorer VII along chosen lines of force or magnetic shells. For interpretation, see text (courtesy of PIZZELLA).

particles moving at such a pitch angle that they would have reached the F-region of the ionosphere (KRASSOVSKI *et al.*, 1961). This was the first direct indication that geomagnetically trapped particles might be of importance to atmospheric phenomena as had been suggested in the first report of their discovery (VAN ALLEN, 1958). Soon after the Orange nuclear explosion (Section 6) the Explorer IV detectors found a butterfly-type angular distribution as fission fragments fed new electrons to the region (JOHNSON and DYCE, 1960). Angular distributions have also been measured by CLADIS *et al.* (1961) on a rocket flight and by O'BRIEN (1962a) with Injun I.

Studies with Explorer IV of the artificial radiation belts produced by the 1958 series of high altitude nuclear explosions (Section 6) provided important information on decay rates of trapped particles, on the configuration of magnetic shells of trapped particles and on their variation with time, and so on (VAN ALLEN *et al.*, 1959b).

3.4 THE CONSTITUENT PARTICLES

Explorer IV was the first to investigate the radiation zones with a set of discriminating detectors. However, in their major paper dealing with Explorer IV data, the Iowa group (VAN ALLEN, MCILWAIN and LUDWIG, 1959a) wrote: "We regard it as unwise at this time to attempt a definitive statement concerning the composition of the radiation and the (energy) spectra of the several components." However, they did find that in the inner zone there was a very penetrating component, and the definitive rocket flight measurement with nuclear emulsions by FREDEN and WHITE (1959) showed that this component was dominantly high energy protons. Most of the counts of the geiger tubes in Explorer IV for $L < 2.0$ were caused by these protons, and their distribution in (L, B) space is shown in Figures 1 and 2 (MCILWAIN, 1961). FREDEN and WHITE (1959) found protons with energy as great as about 600 MeV in the inner zone.

The rocket flights of HOLLY and JOHNSON in early 1959 showed with magnetic separation of the radiation, that the most numerous energetic particles in the inner zone were electrons, and that the energy spectrum and the range distribution decreased monotonically (JOHNSON and HOLLY *et al.*, 1961).

The pulse scintillator in Explorer IV showed that there were intense fluxes of high energy ($E_e \gtrsim 600$ keV) electrons in the inner zone (MCILWAIN, private communication; VAN ALLEN, 1962) although no detailed analysis of these fluxes has been published yet.

The D.C. scintillator on Explorer IV found fluxes of particles up to ~ 76 ergs cm^{-2} sec^{-1} $sterad^{-1}$ in the inner zone (VAN ALLEN *et al.*, 1959a). At first it was assumed that most of this energy flux was due to electrons which were assumed to be generally soft and this led to estimates that the peak electron flux was $j(E_e \gtrsim 20 \text{ keV}) \approx \approx 2 \times 10^9 \text{cm}^{-1}$ (VAN ALLEN, 1959). However, the discovery with Injun I of an intense flux of low energy protons or ions (FREEMAN, 1962) has indicated that some of the D.C. scintillator response in Explorer IV may have been due to such particles, in which case the flux of electrons would be significantly less than the above value (MCILWAIN, private communication). Also, of course, the estimate of particle number from the energy flux is critically dependent on the choice of average electron energy. Combination of available data indicates that the spectrum is relatively flat (Section 5), so that the estimate above may be considerably too large. These matters are not certain, and the problem cannot be resolved now until the artificial radiation zone (Section 6) wears away.

Until the rocket flight of CLADIS *et al.* (1961), definitive information on the constituents of the *outer* zone was lacking. It was recognized that a shielded geiger counter as in Pioneer III and Pioneer IV could count penetrating (i.e. energetic) protons and electrons with high efficiency (of order unity) or *Bremsstrahlung* (from electrons stopping in the shielding) with very low efficiency.

Estimates of very large fluxes of low energy electrons in the outer zone were given (VAN ALLEN, 1959) as $J(E_e \gtrsim 20 \text{ keV}) \approx 10^{10}$ to 10^{11} cm^{-2} sec^{-1} under the explicit assumption that the geiger tubes in Pioneer III and Pioneer IV responded mainly to *Bremsstrahlung* produced in their shielding by low energy electrons, rather than to directly-penetrating higher energy particles. This assumption was unjustified, and it has since been shown to be false (O'BRIEN *et al.*, 1962a), and although in the early studies by the Iowa group it was always stated to be an explicit *assumption*, the above flux estimates tended to be quoted often without any restrictions. Consequently, it was often suggested, for example, that the outer zone trapped particles might be the direct cause of auroras when they emptied into the atmosphere.

The Lunik I scintillator data strongly indicated that the fluxes of low energy electrons in the outer zone were very much less than the figures above (see analysis by DESSLER, 1960; DESSLER, 1961), but the Soviet interpretation of their data gave fluxes essentially the same as above (VERNOV and CHUDAKOV, 1960).

Data from an ion trap on Lunik II showed that (during the passage of the probe) the peak flux in the heart of the outer zone was $J(E_e \gtrsim 200 \text{ eV}) \lesssim 2 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ and it was suggested explicitly that the earlier high estimates from geiger tube data were in error because the tubes were actually measuring very energetic electrons (GRINGAUZ *et al.*, 1961). This was indeed proven to be the case when an electron spectrometer was flown with other apparatus through the region in Explorer XII (O'BRIEN *et al.*, 1962a).

Until mid-1961 most of the definitive information about the content of the radiation zones (as distinct from their spatial and temporal variations), came from combinations of detectors on Explorer IV, Lunik II and rocket explorations (FREDEN and WHITE, 1959; CLADIS *et al.*, 1961; NAUGLE and KNIFFEN, 1961; and others – see Table 2).

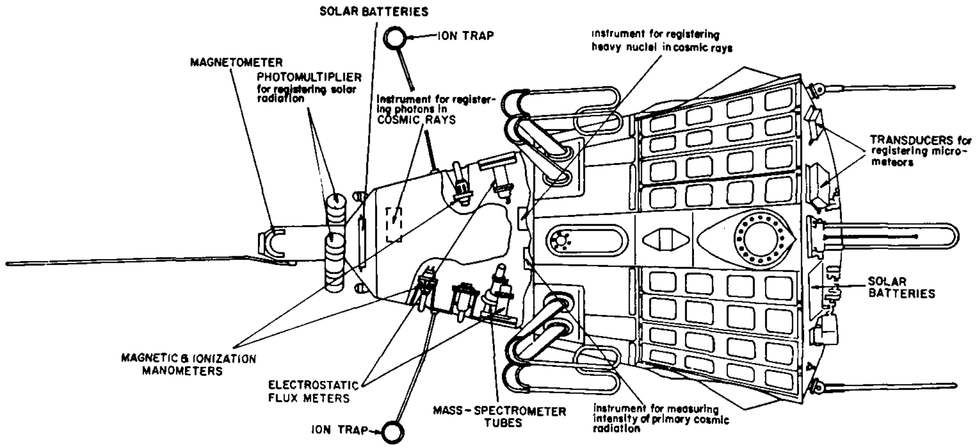
Analysis of data from experiments on Explorer VI and VII, for example, was very critically dependent on the assumptions made about the type and energy spectrum of the particle fluxes being investigated (see Section 7). Both satellites were used to study temporal variations (ARNOLDY *et al.*, 1960a; FORBUSH *et al.*, 1962a) and theories developed to explain the variations without it being known exactly what it was that was changing.

Explorer XII analysis showed that, if electrons with energy $E \geq 40$ keV were measured, there were not two distinct radiation zones but instead one with varying electron spectra (O'BRIEN and LAUGHLIN, 1962a; ROSSER *et al.*, 1962). Furthermore, with this satellite, fluxes of low energy protons were found at $L \geq 2$ in intensities comparable with the electron intensities (DAVIS and WILLIAMSON, 1962). The outermost boundary of trapping of both classes of particles was at variable radial distances of $\sim$ 8 to 11 earth radii, at about the same position as the outermost boundary of the geomagnetic field where it merged with interplanetary space (CAHILL and AMAZEEN, 1962). Thus the whole of this trapping region is occupied by low energy electrons ($E_e \gtrsim 40$ keV) and protons ($E_e \gtrsim 100$ keV) in crudely comparable intensities. The formerly adopted terms of inner and outer zones are now used for convenience rather than necessarily to indicate a different origin.

The rocket flight of CLADIS *et al.* (1961) with a magnetic spectrometer was the first to study the electron spectrum of the outer zone and, at the same time, establish that the particles in question were indeed electrons.

Measurements of electron spectra in the range $40 \leq E_e \lesssim 110$ keV were made later by Explorer XII in the equatorial plane and by Injun I at 1000 km altitude for $L \gtrsim 2$, and these showed temporal variations in the spectra and a general tendency to softer spectra with increasing L (O'BRIEN and LAUGHLIN, 1962a). Other satellite measurements of electron spectra with magnetic spectrometers were made using Discoverers 29 and 31 (WEST *et al.*, 1962). A similar tendency towards softer spectra as L increases is seen with proton fluxes (DAVIS and WILLIAMSON, 1962; MCILWAIN and PIZZELLA, 1962).

Injun I carried a thin windowed geiger tube into the inner and outer zones and so for the first time measured, with essentially unity efficiency, the number flux of low energy electrons with $E_e \geq 40$ keV and protons with $E_p \gtrsim 500$ keV (O'BRIEN *et al.*, 1962b; FRANK and VAN ALLEN, 1962).



Sketch of Sputnik III payload. This weighed more than one ton, was about 12 feet long and five feet in diameter at its base. (After N.A.S.A. Technical Note D-601, March 1961).

FREEMAN (1962) reported findings from Injun I that there was an extremely intense flux of low energy protons (400 ev $\leq E_p \leq$ 500 keV) or ions of similar rigidity trapped in the inner zone. No further investigations of these unexpected particles are known to us, and the presence now in the same regions of many energetic electrons in the artificial radiation belt (Section 6) offers a real challenge for an experimentalist who wishes to study these low energy ions further.

4. Positively-Charged Trapped Particles

4.1 PROTONS WHICH PENETRATE $\sim$ 1 g cm^{-2}

Rocket flights of nuclear emulsions (FREDEN and WHITE, 1959) show that for L $\lesssim$ 2.0, the dominant contribution to the counting rates of the geiger tubes on Explorer IV was from protons. The spatial distribution of counting rates of these geiger tubes as shown in Figures 1 and 2 is therefore the *spatial distribution* of penetrating protons (MCILWAIN, 1961). On the assumption that such protons also dominate the geiger tube rate on Explorer VII, Figure 3 represents the altitude dependence of proton intensity along a line of force (PIZZELLA *et al.*, 1962a). Contamination of this rate by high energy electrons is possible.

On the reasonable assumption that all counts are due to protons, the relevant numbers to convert counting rates to intensities are:

Figure 1. Explorer IV shielded geiger, proton threshold 43 MeV, geometric factor 0.62 cm^2 (MCILWAIN, 1961).

Figure 2. Explorer IV unshielded geiger, proton threshold 31 MeV, geometric factor 0.54 cm^2 (McILWAIN, 1961).

Figure 3. Explorer VII type 302 geiger, proton threshold 18 MeV, geometric factor 0.65 cm^2 (LUDWIG and WHELPLEY, 1960).

Using the above assumption VAN ALLEN (1959) found the peak intensity of penetrating protons at $L \approx 1.4$ to $L \approx 1.5$ in the equatorial plane to be the following:

$$J(E_p \gtrsim 40 \text{ MeV}) \approx 2 \times 10^4 \text{ cm}^{-2} \text{ sec}^{-1}.$$

The measurements with Explorer VI by FAN *et al.* (1960) show

$$J(E_p \gtrsim 75 \text{ MeV}) \lesssim 1 \text{ cm}^{-2} \text{ sec}^{-1}$$

for $L \gtrsim 2.5$.

The principal references for the *proton energy spectrum* are FREDEN and WHITE (1962), NAUGLE and KNIFFEN (1961), and McILWAIN and PIZZELLA (unpublished, 1962).

The spectrum at altitudes of $\approx$ 1000 to 1200 kilometers at $L \approx 1.4$ is of the form (FREDEN and WHITE, 1959)

$$j(E_p)\,\mathrm{d}E \approx E_p^{-1.8}\,\mathrm{d}E$$

for 75 MeV $\leq E_p \lesssim$ 700 MeV integrating the proton flux over the rocket trajectory.

ARMSTRONG *et al.* (1961) found an anomalously large intensity at $E_p \approx 80$ MeV which they considered at first might be a transient effect perhaps caused by solar protons. When they found the same peak more than a year later, they considered it a permanent feature (HECKMAN and ARMSTRONG, 1962). However, since FREDEN and WHITE (1962) exposed an emulsion on the same flight (see Table 2) and did not find this peak, the exact shape of the curve around $E_p \approx 80$ MeV must be considered uncertain.

At lower energies the spectrum becomes systematically softer as L increases. This was first found by NAUGLE and KNIFFEN (1961) who obtained

$$j(E_p)\,\mathrm{d}E \sim E_p^{-4.5 \pm 0.5}\,\mathrm{d}E$$

for 10 MeV $\leq E_p \lesssim$ 50 MeV at $L = 1.79$, $B = 0.23$ Gauss

$$j(E)\,\mathrm{d}E \sim E^{-1.7 \pm 0.3}\,\mathrm{d}E$$

for 40 MeV $\leq E_p \leq$ 100 MeV at $L = 1.53$, $B = 0.209$ Gauss.

Indeed, McILWAIN and PIZZELLA (1962) analyzed the Explorer IV geiger tube data and found a systematic spectral variation with L, which could be fitted by an exponential spectrum

$$j(E_p)\,\mathrm{d}E = \text{constant } \mathrm{e}^{-E/E_0}\,\mathrm{d}E$$

with

$$E_0 = (306 \pm 28)\, L^{-(5.2 \pm 0.2)} \text{ MeV}$$

This spectrum was a reasonable fit to other measurements right out to $L \approx 8$.

4.2 POSITIVELY-CHARGED PENETRATING PARTICLES OTHER THAN PROTONS

The experiments of FREDEN and WHITE (1960) showed that there were very few penetrating particles heavier than protons trapped in the inner radiation zone.

Accordingly, determination of the exact proportion becomes a difficult problem because of possible contamination of the measurements by heavy particles produced in the payload itself by the intense primary proton flux.

Two emulsion groups have given attention to this problem (FREDEN and WHITE, 1960; HECKMAN and ARMSTRONG, 1962). They have used different criteria for the selection of tracks to be studied, and hence their data refer to somewhat different energy ranges. The reader is referred to the original studies for the several criteria and energy intervals studied.

Ignoring these differences, we have grouped all the data together for approximate energy intervals in Table 3.

TABLE 3

RELATIVE PROPORTIONS OF HEAVY ENERGETIC IONS TRAPPED IN THE INNER ZONE

Particle	*Number of Tracks*	*Precentage*
Proton ($E \gtrsim$ 35 MeV)	1270	99 %
Deuteron ($E \gtrsim$ 50 MeV)	6	~ 0.5%
Triton ($E \gtrsim$ 60 MeV)	5	~ 0.5%
$Z = 2$ ($E \gtrsim$ 125 MeV)	None	$\lesssim$ 0.1%

According to FREDEN and WHITE (1960), their observed intensity of tritons was essentially what they would predict if all the tritons were secondary products of nuclear interactions of primary trapped protons with atmospheric constituents. FREDEN and WHITE (1960) detected only 1 deuteron and 5 tritons amidst 492 protons, whereas on the above hypothesis they would predict roughly equal intensities of deuterons and tritons. The problem was alleviated when HECKMAN and ARMSTRONG (1962) found 778 protons with five deuterons and no tritons, so that apparently the anomaly in the early result was simply a matter of inadequate statistics, a problem not infrequent in nuclear-emulsion work.

The relative concentrations of heavy nuclei ($Z \geq 1$) in the geomagnetically trapped radiation are of course of very great interest in theoretical studies of the origin of the radiation, which we do not discuss here.

4.3 POSITIVELY-CHARGED PARTICLES WHICH DO NOT PENETRATE ~ 1 g cm^{-2}

In the inner radiation zone at an altitude of about 1000 kilometers, there was in July 1961 an extremely intense flux of low energy protons or heavy ions. From instrumentation on the Injun I satellite, it was found that these particles reached a peak directional flux

$$j(400 \text{ eV} \lesssim E_p \lesssim 500 \text{ keV}) \approx 60 \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1},$$

where E_p is the energy of the particles if they were protons (FREEMAN, 1962). If they were heavier ions, they must have had similar rigidity to that of protons in the above energy range.

The very low energy ions above were confined to much the same portion of the Injun I orbit (at ~ 1000 km altitude) as the penetrating protons of the inner zone (FREEMAN, private communication).

At higher values of L, for example $L \approx 2.5$ and an altitude of ~ 4800 kilometers, BAME *et al.* (1961) found the following spectra (assuming that the heavy ions they measured were dominantly protons)

$$j(E_p)\,\mathrm{d}E \approx E_p^{-5.2}\,\mathrm{d}E \text{ for } 1.02 \leq E_p \lesssim 2.24 \text{ MeV},$$
$$\text{and } J(E_p)\,\mathrm{d}E \approx E_p^{-3.9}\,\mathrm{d}E \text{ for } 2.24 \text{ MeV} \lesssim E_p \lesssim 7.3 \text{ MeV}.$$

Their data are reasonably similar to extrapolations of the NAUGLE and KNIFFEN (1961) data to lower energies.

The Explorer XII experiment of DAVIS and WILLIAMSON (1962) conclusively established the existence of low energy protons trapped throughout the whole magnetosphere from $L \approx 2$ to the interface ($L_{\max}$) of the magnetosphere with interplanetary space, which was found at radial distances of ≈ 8.5 to ≈ 11 earth radii on the side of the earth towards the sun.

Their peak intensity of protons was found to be

$$j(100 \text{ keV} \lesssim E_p \leq 4.5 \text{ MeV}) \approx 6 \times 10^7 \text{ cm}^{-2}\,\text{sec}^{-1}\,\text{sterad}^{-1} \text{ at L} \approx 3.5.$$

The proton spectra became progressively softer with increasing radial distance, and if approximated by the form exp $(-E/E_0)$, for example, they found

$E_0 = 400$ keV at 2.8 earth radii,
$E_0 = 120$ keV at 5.0 earth radii,
$E_0 = 64$ keV at 6.1 earth radii.

These variations are consistent with extrapolation of the empirical relation derived by MCILWAIN and PIZZELLA (1962), and from a general viewpoint, this may be taken as evidence for completely abandoning any concept of an inner and outer radiation zone as having different origins. The proton flux was somewhat affected by a magnetic storm.

There is also some evidence of ions heavier than protons trapped in this region, but data analysis is still preliminary only (DAVIS, private communication).

4.4 SUMMARY OF MEASUREMENTS OF POSITIVELY-CHARGED TRAPPED PARTICLES

4.4.1 *Composition*

For $L \lesssim 2$, and $E \gtrsim 1$ MeV, the positively charged constituents of the radiation zones are about 99 % protons, 0.5 % deuterons, and 0.5 % tritons, with less than 0.1 % heavier nuclei. The ionic composition of the particles with $E \leq 1$ MeV found by FREEMAN (1962) at $L \lesssim 2$ in unknown. The ionic composition of energetic positively charged particles at $L \gtrsim 2$ is uncertain, but many of them are protons.

4.4.2 *Spectrum*

Apart from the particles found by FREEMAN (1962), there is an indication that the energy spectrum of the positively charged component varies smoothly with L, following an exponential spectrum $j(E_p)$ constant $e^{-E/E_0}\,dE$ with an empirical relation

$$E_0 = (306 \pm 28)\, L^{-(5.2 \pm 0.2)}\ \text{MeV}$$

from

$$L \approx 1.2 \text{ to } L \approx 8 \text{ (McIlwain and Pizzella, 1962).}$$

4.4.3 *Intensity*

The peak intensity of energetic protons ($E \gtrsim 40$ MeV) is found between L $\approx$ 1.4 and $\approx$ 1.5 and it is

$$J(E_p \gtrsim 40\ \text{MeV}) \sim 2 \times 10^4\ \text{cm}^{-2}\ \text{sec}^{-1}$$

in the equatorial plane (Van Allen, 1959).

The peak intensity of less energetic protons for $L \gtrsim 2$ is found at $L \approx 3.5$ earth radii and is

$$j(100\ \text{keV} \leq E_p \leq 4.5\ \text{MeV}) \approx 6 \times 10^7\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{sterad}^{-1}$$

(Davis and Williamson, 1962).

The peak energy flux measured to date from heavy ions at $L \approx 1.5$ and an altitude of $\sim$ 1000 kilometers is

$$j(400\ \text{ev} \leq E_p \lesssim 500\ \text{keV}) \approx 60\ \text{ergs cm}^{-2}\ \text{sec}^{-1}\ \text{sterad}^{-1}$$

(Freeman, 1962).

4.4.4 *Spatial Distribution*

Reference may be made to McIlwain (1961), Pizzella *et al.* (1962a) and Fan *et al.* (1960) and to Figures 1, 2, 3 for the spatial distribution of energetic protons ($E_p \gtrsim 20$ MeV).

Reference may be made to Freeman (1962) and to Davis and Williamson (1962) for the spatial distribution of the lower energy protons or heavy ions.

5. Electron Fluxes

5.1 GENERAL

Because the high-altitude nuclear explosion of July 9, 1962 caused great numbers of fission-decay and neutron-decay electrons to be trapped, discussion of the electrons trapped prior to the explosion is now somewhat academic. In this section, the "natural" electrons are discussed, and in the next section the artificially-injected electrons are treated.

Accurate measurement of electron fluxes is difficult (*a*) in the inner zone because of the high intensity of penetrating protons and (*b*) in the outer zone because of variations of the electron energy and spectrum with time. In the following we are forced to assume that in the heart of the inner zone the electron spectrum and intensity are constant in time. There is no experimental evidence relating to this assumption.

5.2 INNER-ZONE ELECTRONS ($L < 2.0$)

There are no observations of the *spatial distribution* of inner zone electrons which compare in reliability and extent with the equivalent proton observations. However,

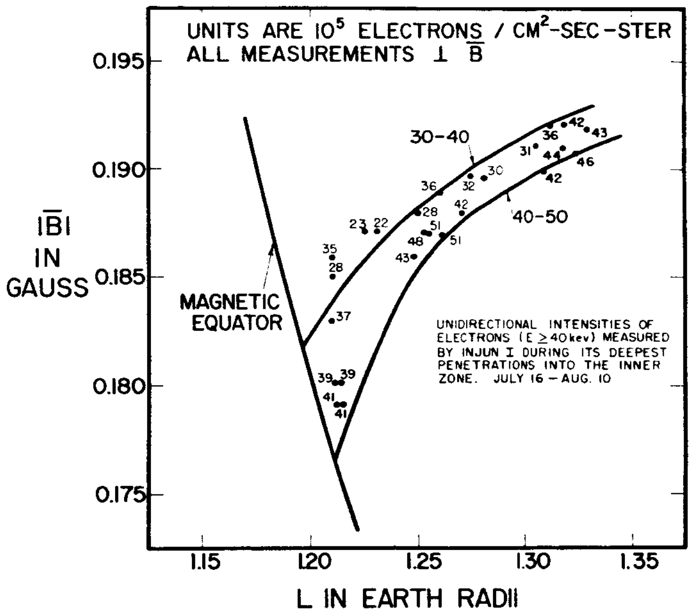


Fig. 4. Counting rate contours of the type 213 geiger tube in Injun I when it was measuring electrons with $E_e \gtrsim 40$ keV moving at right angles to B (courtesy of L. A. FRANK).

FRANK and VAN ALLEN (1962) show a plot over a small range of (B, L) coordinates of data from the Injun I satellite at 1000 km altitude which is reproduced in Figure 4. The quoted directional intensities are those of both electrons with $E_e \gtrsim 40$ keV and protons with $E_p \gtrsim 500$ keV, but data from other detectors on the same satellite indicate that the electron flux is the dominant one (FRANK and VAN ALLEN, 1962).

VAN ALLEN (1962) states that the spatial distribution of electrons with $E_e \gtrsim 600$ keV measured with Explorer IV is similar to that of energetic protons seen with the same satellite, but that the electrons spread to somewhat higher latitudes. Comparison of Injun I data (FRANK and VAN ALLEN, 1962) with those of HOLLY *et al.* (1961) also indicates that the intensity of electrons with $E_e \gtrsim 40$ keV does not decrease with increasing L or B as rapidly as does that of energetic protons with $E_p \gtrsim 40$ MeV or $E_p \gtrsim 31$ MeV shown in Figures 1 and 2, taken from MCILWAIN (1961). Explorer XII data indicate the same effect (ROSSER *et al.*, 1962) with little or no "slot" for electrons with $E_e \gtrsim 40$ keV at $L \sim 2$. Further data analysis is essential before the detailed spatial distribution of electrons with $E_e \gtrsim 40$ keV in the equatorial plane for $L \lesssim 3$ will be known.

While numerous measurements of the *electron intensity* in thc inner zone have been made as listed in Table 4, we consider the results relatively uncertain. As discussed in Section 7, the estimate for the heart of the inner zone of

$$j(E_e \gtrsim 20 \text{ keV}) \approx 2 \times 10^9 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1},$$

derived from the D.C. scintillator in Explorer IV (VAN ALLEN and FRANK, 1959b) is probably too high an estimate by a factor of about ten.

If the value $j(E_e \gtrsim 40 \text{ keV}) \approx 4 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$ for $L = 1.20$ on the equator is taken from Figure 4 (courtesy of L. A. FRANK), and normalized tot he heart of the inner zone $L \sim 1.45$ on the equator by using *proton* data from Figure 1 (courtesy of C. E. MCILWAIN), then we would find for the heart of the inner zone

$$j(E_e \gtrsim 40 \text{ keV}) \approx 3 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1},$$

if it is assumed that electron and proton spatial distributions from $L \approx 1.2$ to $L \approx 1.45$ in the equatorial plane are similar. Such an assumption is questionable, but it is crudely valid (to a factor of about two) for MCILWAIN's measurements of electrons with $E_e \gtrsim 600$ keV, and so it is used here.

MCILWAIN (private communication) finds for the heart of the inner zone

$$j(E_e \gtrsim 600 \text{ keV}) \gtrsim 2 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1},$$

which is only ten times less than $j(E_e \gtrsim 40 \text{ keV})$ listed above. Yet the spectrum of HOLLY *et al.* (1961) taken on the same shell at a considerably lower altitude ($B = 0.25$ gauss) would have

$$\frac{j(E_e \gtrsim 40 \text{ keV})}{j(E_e \gtrsim 600 \text{ keV})} \approx 1000.$$

Several *electron spectra* are shown in Figure 5 (courtesy IMHOF and SMITH) to illustrate the experimental spread.

Since the scintillator on Explorer VI used in the estimate of electron intensity by HOFFMAN *et al.* (1962) cannot discriminate between the two estimates listed in Table 4, and since the rocket experiments were at too low an altitude, we are forced to combine Injun I and Explorer IV data and obtain the following estimates for the heart of the inner zone.

$$j(E_e \gtrsim 40 \text{ keV}) \approx 10^8 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$$

and

$$j(E_e \gtrsim 600 \text{ keV}) \approx 10^6 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$$

where the uncertainty is at least a factor of three in each case.

A crude check on the above estimates can be made by taking the electron spectrum of IMHOF *et al.* (1962) shown in Figure 5 and normalizing it to the heart of the inner

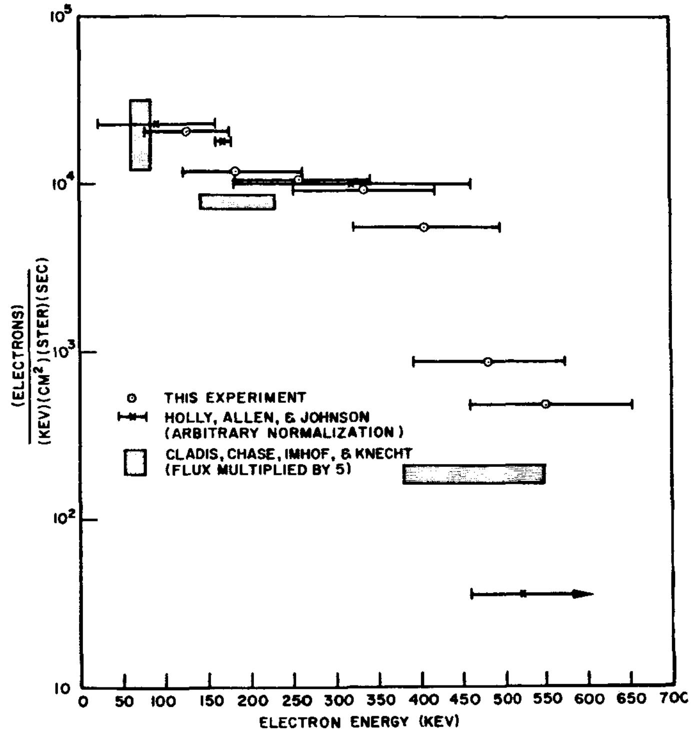


Fig. 5. Normalized electron spectra measured in the inner zone (IMHOF *et al.*; HOLLY *et al.*) and in the outer zone (CLADIS *et al.*) with rocket flights (courtesy of W. IMHOF and R. SMITH).

zone by combining the proton intensity measured on the same flight with MCILWAIN's Explorer IV data of Figure 1. The resultant fluxes are about

$$j(E_e \gtrsim 80\ \text{keV}) \approx 7 \times 10^7\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{sterad}^{-1}$$

and

$$j(E_e \gtrsim 450\ \text{keV}) \approx 10^6\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{sterad}^{-1}$$

in surprisingly good agreement with the above estimates.

Samples of the *electron spectrum* at relatively low altitudes are shown in Figure 5. The scatter of points is large. The outer-zone measurements of CLADIS *et al.* (1961) are included for comparison with the inner-zone values. The spectral measurements by PIZZELLA *et al.* (1962b) at 1000-km altitude are consistent with a power-law spectrum with a differential exponent of $-(1.0 \pm 0.2)$ for 40 keV $\lesssim E_e \lesssim$ 110 keV, and thus are in moderate agreement with Figure 5.

The spectral measurements appear adequate to refute the neutron-albedo origin hypothesis in its presently-developed form (see HOLLY *et al.*, 1961; PIZZELLA *et al.*,

TABLE 4

REPORTED NATURAL ELECTRON INTENSITIES AT $L \lesssim 2$ (in the inner belt)

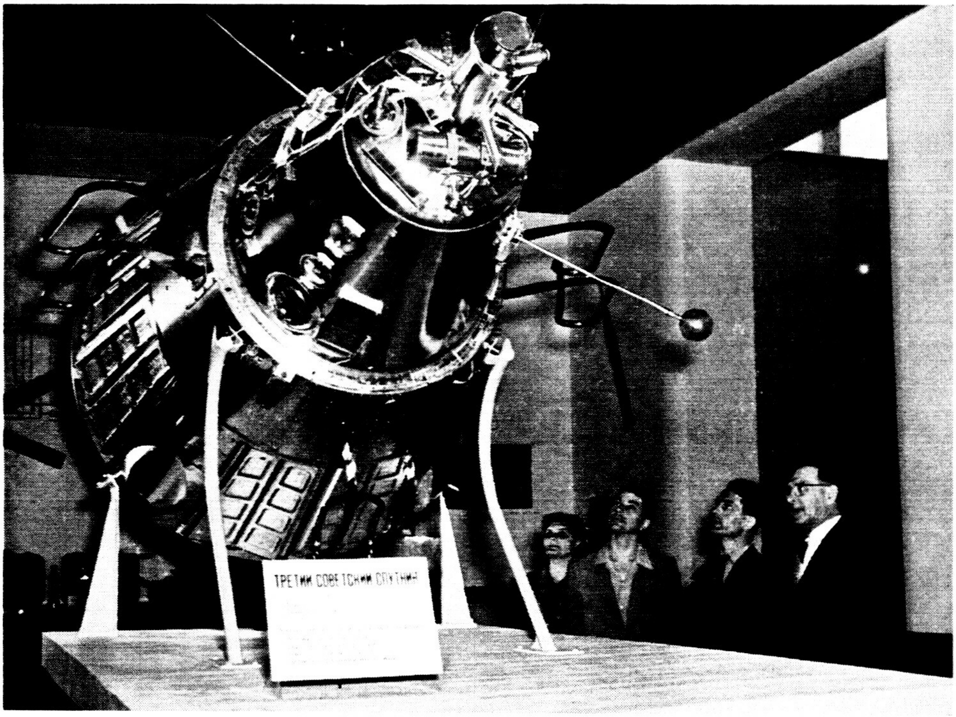
Energy Range	*Intensity*	*Technique*	*L, B*	*Reference*
$E_e \gtrsim$ 20 keV	$j = 2 \times 10^9$	See Text	Peak	VAN ALLEN and FRANK (1959b)
$E_e \gtrsim$ 40 keV	$j = 5 \times 10^6$	Geiger	Range (see Figure 5)	FRANK and VAN ALLEN (1962)
$E_e \gtrsim$ 30 keV	$j = 8 \times 10^5$	Geigers	$L = 1.50$ $B = 0.25$ gauss	HOLLY *et al.* (1961)
$E_e \gtrsim$ 80 keV	$j \approx 5 \times 10^6$	Spectrometer		IMHOF *et al.* (1962)
$E_e \gtrsim$ 160 keV	$j \approx 5 \times 10^5$	Geigers	$L = 1.50$ $B = 0.25$	HOLLY *et al.* (1961)
$200 \leqslant E_e \leqslant 500$ keV	$j = 2 \times 10^9$	Scintillator	8600 km radial distance and −28.4. Mag.	HOFFMAN *et al.* (1962)
or	*or*			
$E_e \gtrsim$ 500 keV	$j = 1 \times 10^7$	Scintillator		HOFFMAN *et al.* (1962)
$E_e \gtrsim$ 600 keV	$j = 1 \times 10^7$	Scintillator	$L \approx 1.4$ Equator	VAN ALLEN (1962)
$E_e \gtrsim$ 600 keV	$j \gtrsim 2 \times 10^6$	Scintillator	$L \approx 1.5$ Equator	MCILWAIN (private communication)
$E_e \gtrsim$ 12 MeV	$j \lesssim 0.01$ J ($E_p \gtrsim 70$ MeV)	Emulsions	Range (see ref.)	FREDEN and WHITE (1959)

TABLE 5

NUCLEAR DEVICES DETONATED AT HIGH ALTITUDES

Code Name	*Explosive Power*	*Altitude*	*Date*	*Reference*
Teak	?	76 km	Aug. 1, 1958	JOHNSON and DYCE (1960)
Orange	?	44 km	Aug. 12, 1958	
Argus I	1–2 kilotons	Nominal 480 km	Aug. 27, 1958	
Argus II	1–2 kilotons	Nominal 480 km	Aug. 30, 1958	VAN ALLEN *et al.* (1959b)
Argus III	1–2 kilotons	Nominal 480 km	Sept. 6, 1958	
Starfish	1.4 megatons	400 km	July 9, 1962	O'BRIEN *et al.* (1962c)

1962b), but they are generally unsatisfactory. In particular they do not resolve the important problem of whether there are any naturally-occurring inner-zone electrons with energies greater than 780 keV, the maximum energy of the neutron beta-decay spectrum. Now that there are intense fluxes of energetic fission electrons in the same region, it will be impossible to resolve this problem for many years (see Section 6).



Close-up of Sputnik III "solar-radiation" detectors (see also the Figure on page 444). These are two scintillators, detectors (a) and (b) in Table I.

The existing inner-zone spectral measurements will therefore have to be used. We consider that they should be used with care.

5.3 OUTER-ZONE ELECTRONS ($L \gtrsim 2$)

In the region $L \gtrsim 2$, the electron fluxes vary greatly in intensity, spectrum and spatial distribution with time. Several generalizations of their characteristics are made below, but in each case the original references should be studied for the detailed behavior. Historically the studies have been confused because the particle detectors have often been far from ideal (see Section 7).

The spatial distributions of energetic electrons at particular times are faily well measured. Lunik II and III (VERNOV and CHUDAKOV, 1960a and b; GRINGAUZ *et al.*, 1961), Pioneer III and IV (VAN ALLEN and FRANK, 1959a and b), Explorer VI (ARNOLDY *et al.*, 1962; SIMPSON *et al.*, 1962), and Explorer XII (ROSSER *et al.*, 1962) have explored the outer zone in the equatorial plane at high altitudes, while Injun I (O'BRIEN, 1962b) and Discoverers (HESS *et al.*, 1962) have explored it at relatively low altitudes. It is clear that, in the equatorial plane for electrons with $E_e \gtrsim 40$ keV, there is no distinction into the inner and outer radiation zones with a "slot" between as suggested by early data from shielded geiger tubes (VAN ALLEN and FRANK, 1959 a and b). Instead, the intensity of such electrons remains the same within perhaps an order of magnitude from $L \approx 2$ to the outer boundary of trapping ($L_{\max}$) at radial distances of $\approx$, 65,000 kilometers on the local noon side of the earth, with $J(E_e \gtrsim 40 \text{ keV}) \approx 10^7$ cm^{-2} sec^{-1} in equatorial plane for $2 \leq L \lesssim L_{\max}$ (ROSSER *et al.*, 1962; O'BRIEN, 1962b). GRINGAUZ *et al.* (1961) found a "third radiation zone" with a plasma probe at 11 earth radii where

$$J(200 \text{ ev} \leq E_e \leq 20 \text{ keV}) \approx 10^8 \text{ cm}^{-2} \text{ sec}^{-1} .$$

O'BRIEN (1962b) shows several hundred measurements as a function of L over North America, and finds at 1000 km altitude that the *average* intensity

$$j(E_e \gtrsim 40 \text{ keV}) \approx 10^5 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$$

for

$$2 \lesssim L \lesssim L_{\max} .$$

The intensity at lower altitudes is strongly dependent on time and magnetic latitude (O'BRIEN, 1962b).

Changes in electron intensity with time can be very great. In the equatorial plane, $J(E_e \gtrsim 40 \text{ keV})$ can change by an order of magnitude in less than a day (O'BRIEN, 1962b). The higher energy electrons can change by three orders of magnitude in the same time, so that

$$J(E_e \gtrsim 1.5 \text{ MeV}) \approx 10^3 \text{ to } 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$$

(ROSSER *et al.*, 1962).

At lower altitudes, where only particles with small equatorial pitch angles (α_0) are detected, the changes in intensity of $E_e \gtrsim 40$ keV with time can be as great as one million in about thirty seconds (or while the satellite moved about 200 kilometers) (O'BRIEN and LAUGHLIN, 1962a) or by a factor of one thousand in less than one second (or while the satellite moved about 8 kilometers), (O'BRIEN, unpublished). The demands on the adequacy of dynamic range and telemetry capabilities of the apparatus are therefore very great (Section 9).

A few spectral samples of outer zone electrons are shown in Figure 6, and this matter is discussed in some detail in Section 7, because it represents one of the most confused situations in radiation zone measurements since their beginning.

Four groups have reported outer zone spectral measurements (CLADIS *et al.*, 1961; KRASSOVSKII *et al.*, 1961; O'BRIEN and LAUGHLIN, 1962b; WEST *et al.*, 1962). There is a general tendency for the spectrum over the energy range 40 keV $\leq E_e \leq$ 110 keV to become softer as L increases, but there are very marked temporal variations in the spectral slope at a given L (O'BRIEN and LAUGHLIN, 1962a and b). Figure 6 may be taken as a representative spectral sample, illustrating the variation by about fifteen orders of magnitude in the electron intensity over the energy range of interest.

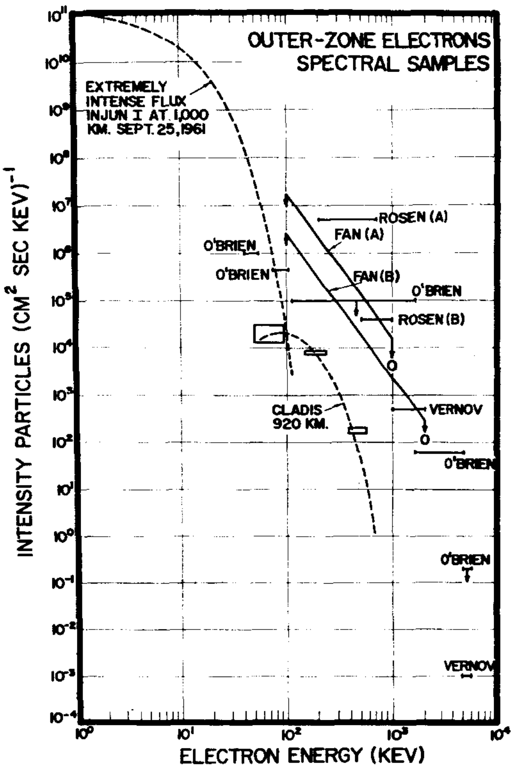


Fig. 6. Sample spectra of outer zone electrons. ROSEN A and ROSEN B depend on whether the Explorer VI scintillator was a directional or an omnidirectional detector (Section 7). FAN A and FAN B are the favored estimates of FAN *et al.* (1961) with two choices according as the maximum electron energy was assumed to be 1 MeV or 2 MeV.

6. Artificial Radiation Belts

Charged particles can be artificially injected into the geomagnetic field at such pitch angles that they become trapped. If sufficient numbers are injected, they may cause a detectable artificial radiation belt (CHRISTOFILOS, 1959). Such belts, created impulsively at a known time and location with an initially-known number of particles, can in principle be of enormous scientific value, enabling study of such phenomena as

i) creation of artificial aurorae,
ii) mapping of magnetic shells and their movement,
iii) study of decay times, etc.

At the time of writing, October 1, 1962, there have been at least six explosions of nuclear devices at high altitudes which created artificial radiation belts of high energy electrons. All the announced attempts have been by the United States, and any comparable efforts by other nations have not been announced publicly.

The six explosions are listed in Table 5.

Teak and Orange were larger in yield than the Argus series, but at much lower altitudes (JOHNSON and DYCE, 1960). The artificial radiation belts they produced were small and disappeared in a few days, because few electrons were injected at such altitudes ($\approx$ 800 km) over the explosion point at Johnston Island that they were able to drift around the world without dipping deeply into the atmosphere in the South Atlantic and being lost.

The Argus explosions were at high geographic altitude, and furthermore were exploded in the South Atlantic, so that the electrons were injected at effectively high *magnetic* altitudes and they produced fairly durable radiation belts and, of course, a variety of other interesting phenomena (see VAN ALLEN *et al.*, 1959b). Their radiation belts were at $L = 1.715$, 2.115 and 2.16 earth radii respectively and provided a very convenient check of the L parameter calculations (MCILWAIN, 1961). Although the explosions were relatively small, they took place in the so-called "slot" between the inner and outer radiation zones, and were clearly detectable with shielded geiger tubes on Explorer IV for some weeks at altitudes below $\sim$2200 kilometers (VAN ALLEN *et al.*, 1959b). They died away at these altitudes, and no reports of their detection with later satellites have been made public.

These belts were of trivial magnitude when compared to that produced by the project Starfish explosion of a large yield device at high altitude over Johnston Island on July 9, 1962. The resultant belt is so intense that its high energy electrons dominate the inner zone at $L \lesssim 1.5$. As a consequence, at the present time the summaries given in Section 4 for the proton fluxes may not be correct, since it has been suggested that some natural protons formerly trapped might have been lost following the explosion. The summaries given in Section 5 for the electron fluxes are certainly not correct, and we briefly summarize the present status as follows, with data taken from the Injun 1 satellite, which fortunately endured long enough after its launch in June 29, 1961 to map out both the new and old environment (O'BRIEN *et al.*, 1962c).

The artificial radiation belt produced by Starfish initially led to large intensities of trapped electrons not only in the region of the natural inner zone, but also at much lower altitudes. In effect it populated the entire region underneath the old natural inner belt, where we can consider qualitatively that the atmosphere had worn down the inner zone intensity or prevented it from becoming high over the preceeding years. Following Starfish, the atmosphere had to wear away the artificial belt from its underside. This it did, effectively removing electrons which mirrored at altitudes as low as 100 to 200 kilometers in a few hours, while the intensity of those with minimum mirror altitudes of about 350 kilometers was greatly reduced in a few weeks. At higher altitudes, however, large intensities still persist several months later, and it appears that the artificial belt will remain at the higher altitudes in measurable intensities for many months (O'BRIEN *et al.*, 1962c).

As yet, neither the intensity of the electrons nor their spatial extent is certain. Their spectrum is at least crudely similar to the fission spectrum, which is of the form

$$N(E)\mathrm{d}E = 3.88 \exp(-0.575\, E - 0.055\, E^2)$$

for the range $1 \leq E \leq 7$ MeV, where E is the electron energy in MeV, and the spectral expression is in units of beta-particles per fission per MeV (CARTER, REINES, WAGNER and WYMAN, 1959). See, however, ALLEN, BEAVERS, WHITAKER, WELCH and WALTON (1959) whose spectral measurements of Argus electrons indicated fewer high energy electrons than a fission spectrum would predict. Only about one half the fission electrons have initial energy $E_e \leq 1$ MeV, and in the following intensity estimates only electrons with $E_e \gtrsim 1$ MeV will be discussed.

Injun I measurements with a geiger tube shielded by more than 3.5 g cm^{-2} of lead showed that the Starfish belt caused counting rates one or more orders of magnitude higher than those caused formerly by penetrating inner zone *protons*. For a preliminary analysis, it was assumed that all the additional counts of this detector were due to penetrating electrons with energy $E_e \gtrsim 6$ MeV, but it is quite possible that most of the counts were due to *Bremsstrahlung* from the more numerous lower energy electrons. Estimates of the intensities of fission electrons with $E_e \gtrsim 1$ MeV happen to be much the same irrespective of which mechanism causes the counts, and this leads to estimates of the peak intensity at $L \approx 1.2$ of

$$J(E_e \gtrsim 1 \text{ MeV}) \approx 10^8 \text{ particles cm}^{-2}\text{ sec.}^{-1}$$

The uncertainty in this estimate is about an order of magnitude.

In Figure 7, taken from the preliminary study of O'BRIEN *et al.* (1962c), the spatial extent of the artificial zone is compared with that of the inner zone. There are only a few measurements by Injun I at the highest altitudes, and the closure of the 10 000 counts per second contour is based on only four points. However, there is no reason to regard the closure as invalid. More detailed high altitude measurements will be necessary before the full radial extent of the artificial belt is known. They must be made with detectors similar to those flown in the same region previously.

For the experimentalist planning radiation-zone measurements in these regions in the next year or more, the Starfish explosion has the following consequences:

i) there is no guarantee that the naturally occurring trapped protons of the inner zone, particularly those of very high energies, were not depleted.

ii) heavy shielding of a detector (e.g. by $\sim$ 1 g cm^{-2} of material) in the inner zone will no longer guarantee that only protons will be detected. Instead, the dominant particles which do penetrate will be energetic ($E_e \gtrsim 1$ MeV) electrons.

iii) the natural electron spectrum cannot be measured for $L \lesssim 2$, and perhaps not at higher L values. In particular an experiment to determine whether there were any inner zone natural electrons with energy above the neutron-decay end point of 780 keV is now impossible.

iv) the fluxes of energetic electrons are so large, i.e. 10^8 and perhaps 10^9 particles cm^{-2} sec^{-1} that the fabrication of a detector *small* enough to count at moderate rates is a formidable technical problem.

v) there is little possibility of further investigation of the low energy ions found by Injun I.

We consider that the publicly-available *scientific* information which can conceivably be gained from study of the Starfish artificial belt (O'BRIEN *et al.*, 1962c) is negligible when compared with the scientific information which is lost because of its existence. Such a judgment, of course, is highly subjective.

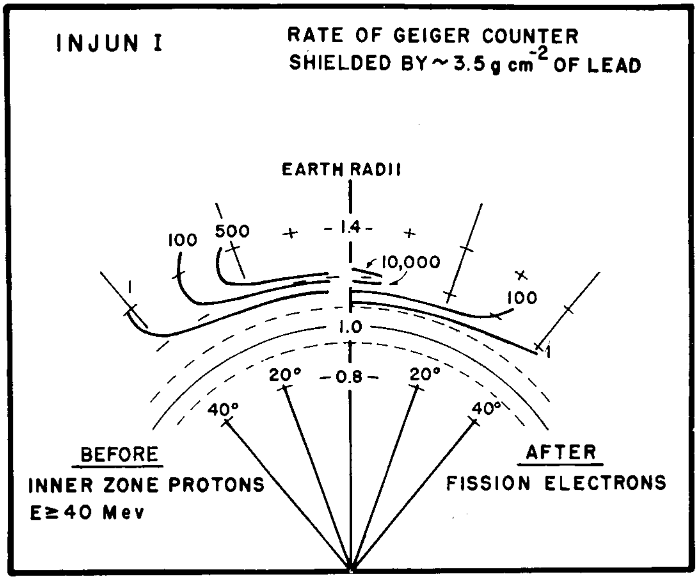


Fig. 7. Illustration in the idealized coordinate system of MCILWAIN (1961) of the effect on the counting rate of a heavily shielded geiger tube in Injun I of the high altitude nuclear explosion of July 9, 1962. The contours on the left were those before the event, where the counts were due to energetic protons of the inner zone and where multiplication of count rate by 9 gives $J(E_p \gtrsim 50$ MeV). The contours on the right were those some six to ten hours after the explosion, where the counts were due to energetic electrons of the artificial radiation belt, where multiplication of count rate by 10 000 to 100 000 gives $J(E_e \gtrsim 1$ MeV) (from O'BRIEN *et al.*, 1962c).

7. Revised Interpretations of Data from Several Satellites

We summarize in this section, briefly and without extensive justification, a listing under each satellite in turn, of revisions of published interpretations of data from that satellite. In many cases, the revisions have been published by the original authors themselves, and these are included here for completeness. In other cases, particularly with more recent data, we have reviewed certain experiments which appear to us to require review.

The purpose of such a summary is to provide a convenient review, satellite by satellite, of published interpretations of data so that, for example, theoreticians not in the usual channels of private communications may avoid basing extensive theories on old experimental papers subsequently found to be invalid in one way or another. The objectivity of this summary may be assessed from the fact that the author's name appears in it.

In very many of the revisions, particularly of interpretations from early exploratory measurements, there is no need at all to consider that they necessarily imply any carelessness on the part of the original workers. In exploring in a new realm, the exciting discoveries are generally made in a qualitative rather than a quantitative experiment. The very existence of the radiation zones was an exciting discovery, and we know of no person who would have preferred that the existence of the zones be not announced until their exact composition was known. Consequently, if, in the following listing of revisions, several names appear more often than others, this may merely be a measure of the fact that they remained in the forefront of discoveries in the field.

EXPLORER I AND EXPLORER III

The original interpretation (VAN ALLEN, 1958) was that the enhanced counting rates of the geiger tubes were dominantly due to *Bremsstrahlung*. They were in fact due to penetrating protons (VAN ALLEN, 1962).

SPUTNIK III

A very intense flux of electrons was judged to be ≈ 4000 ergs cm^{-2} sec^{-1} sterad^{-1} if the average electron energy was taken as 10 keV (KRASOVSKII *et al.*, 1960). If, however, the average energy was 14 keV, the flux would have been only 360 ergs cm^{-1} sec^{-1} sterad^{-1} (KRASOVSKII *et al.*, 1961). Since this measurement was from a single scintillator, with the reading off scale, we suggest that if the electrons were of 20 keV, then the flux would have been $\approx$ 10 ergs cm^{-2} sec^{-1} sterad^{-1}, and so on (see calibration Figure 2, KRASSOVSKII *et al.*, 1961).

EXPLORER IV

Studies of temporal variations in the outer zone by using shielded geiger tubes (ROTHWELL and MCILWAIN, 1960) are subject to several interpretations, since a change in counting rate might result from a variation in the intensity of electrons of a given energy or a variation in the average energy of formerly trapped electrons. This is discussed below for Pioneer III and IV and Explorer VI.

The estimate of the electron flux in the heart of the inner zone

$$j(E_e \gtrsim 20\text{ keV}) \approx 2 \times 10^9\text{ cm}^{-2}\text{ sec}^{-1}\text{ sterad}^{-1}$$

given by VAN ALLEN and FRANK (1959b) and VAN ALLEN (1959) was based on the total energy flux measured there with the D.C. scintillator on Explorer IV, where

$$\text{Flux }((E_e \gtrsim 20\text{ keV}) + (E_p \gtrsim 400\text{ keV})) \approx 100\text{ ergs cm}^{-2}\text{ sec}^{-1}\text{ sterad}^{-1}.$$

Since the existing concept was that the electron spectrum was soft, this energy flux was assumed to be all electrons with an average energy of $\approx$ 30 keV to obtain the value of

$j(E_e \gtrsim 20$ keV) above. Reference to Figure 5 shows that the spectrum is relatively flat, and an average energy of $E_e \approx 200$ keV is more accurate. Thus we find

$$j(E_e \gtrsim 20 \text{ keV}) \approx 3 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1} .$$

Furthermore, since the D.C. scintillator on Explorer IV may have responded to some of the low energy ions or protons found by Injun I (FREEMAN, 1962) the above is

Explorer IV instrument column and GEORGE LUDWIG. The two large cylinders are Detector (a) (with aperture visible) and Detector (b) pointing 180° away from (a). The unshielded geiger tube Detector (c) is above the shielded geiger tube Detector (d) (see Table I), and these geigers are the two small cylinders closest to the reader.

clearly an upper limit. This is the reason we summarized the inner zone peak flux in Section 5 as

$$j(E_e \gtrsim 20 \text{ keV}) \approx 10^8 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$$

with an uncertainty of a factor of three.

PIONEER III AND PIONEER IV

The outer zone detected with geiger tubes on these probes was initially attributed to *Bremsstrahlung* produced in the geigers by low energy ($E_e \gtrsim 20$ keV) electrons in intensities of $\sim 10^{10}$ to 10^{11} particles cm^{-2} sec^{-1} (VAN ALLEN and FRANK, 1959 a and b; VAN ALLEN, 1959). In fact the peak counting rates were due to particles in much lower intensities, and the intensity of electrons with $E_e \gtrsim 40$ keV was 10^8 cm^{-2} sec^{-1} or less (O'BRIEN *et al.*, 1962a). Furthermore, the large changes in counting rate between Pioneer III and IV which were initially attributed to large changes in the intensity of low energy ($E_e \gtrsim 20$ keV) electrons (VAN ALLEN and FRANK, 1959b) were probably caused by a relatively small change in the average energy of the more energetic particles. For example, a doubling of the energy of an electron with $E_e \approx 1$ MeV can cause it to be counted by such geigers with a one-thousand fold increase in efficiency (O'BRIEN, *et al.*, 1962a).

EXPLORER VI

Initial studies by the Minnesota group of electron fluxes and time changes in the outer zone (ARNOLDY *et al.*, 1960 a and b) are subjected to the same alterations as the Pioneer III and IV data on some occasions, but "total fluxes deduced in the heart of

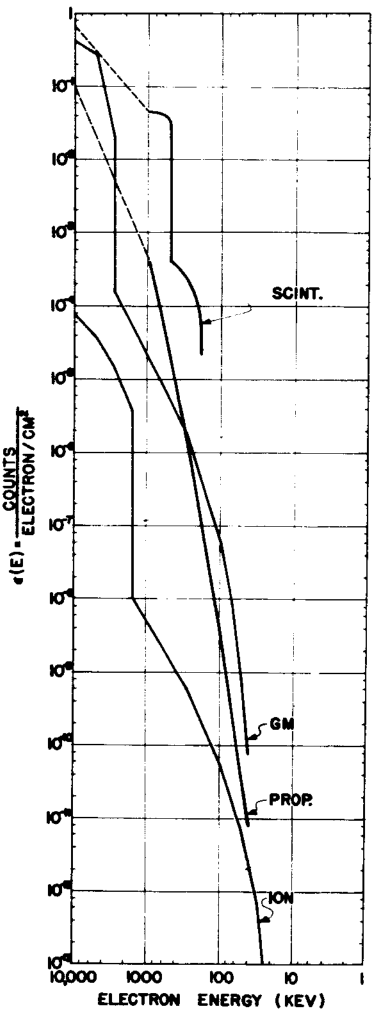


Fig. 8. The efficiencies of the four detectors aboard Explorer VI versus electron energy. The dashed extensions to the scintillator and proportional counter curves are extrapolations. Compare these curves with the outer zone spectral samples of Figure 6 over the same energy range. (Courtesy of ARNOLDY and WINCKLER.)

the outer zone by fitting trial spectra to the Explorer VI data are meaningless" (ARNOLDY *et al.*, 1962).

Where other experimenters with apparatus on Explorer VI used the Minnesota detectors in their analyses, the uncertainties recently expressed by ARNOLDY *et al.* (1962) on outer zone data indicate that the former analyses must be reviewed critically.

For example, the Chicago group used changes in the ratio of counting rate of their "single" proportional counter to that of the Minnesota geiger counter to study changes in the outer zone electron spectrum (FAN *et al.*, 1961; SIMPSON *et al.*, 1962). Qualitatively, a change in the ratio certainly indicates a change in the spectrum, and their conclusions based on the *occurrence* of a change in the ratio are valid. But just what that change is quantitatively is far more difficult to determine. We reproduce in Figure 8 a figure of ARNOLDY *et al.* (1962) to illustrate the complexity of the problem. Many possible spectral forms and their effect on the above ratio are shown in ARNOLDY *et al.* (1962).

The existence in the outer zone of two peaks in the plot of single counting rate versus radial distance led FAN *et al.*, (1960 *et seq.*) to label them as two distinct outer zones E2 and E1. ARNOLDY *et al.* (1962) and others (*e.g.* O'BRIEN *et al.*, 1962a) show that these peaks occur because of an electron spectrum which varies with radial distance. The "radial movement" of these peaks with magnetic activity is attributed to change in the electron spectrum at a given distance (ARNOLDY *et al.*, 1962).

We now review briefly the complex studies made with the Explorer VI plastic scintillator of the Space Technology Laboratory group. In Table 1 of ROSEN and FARLEY (1961) the flux estimates for the outer zone of

$$J(E_e \gtrsim 200 \text{ keV}) \approx 2.2 \times 10^9 \text{ and } 2.7 \times 10^9 \text{ cm}^{-2} \text{ sec}^{-1}$$

and

$$J(E_e \gtrsim 500 \text{ keV}) \approx 1.6 \times 10^7 \text{ and } 2.0 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$$

are *alternative* choices, depending on whether the principal contributions to the counting rate came from electrons entering through the aperture or through the satellite shell. In later analysis (FARLEY and SANDERS, 1962) it is stated that "the scintillation counter is responding entirely to electrons of energies above 500 keV because of the improbably large fluxes of electrons below this energy that would be required to cause a significant fraction of the observed count rate". We show both estimates in Figure 6, and concur with the recent judgment of FARLEY and SANDERS (1962).

Similarly, comparison with other data (Table 4) may decide which of the two estimates of ARNOLDY *et al.* (1962) for the flux of inner zone electrons is valid. They conclude that either

$$J(200 \text{ keV} \leq E_e \leq 500 \text{ keV}) \approx 2 \times 10^9 \text{ cm}^{-2} \text{ sec}^{-1}$$

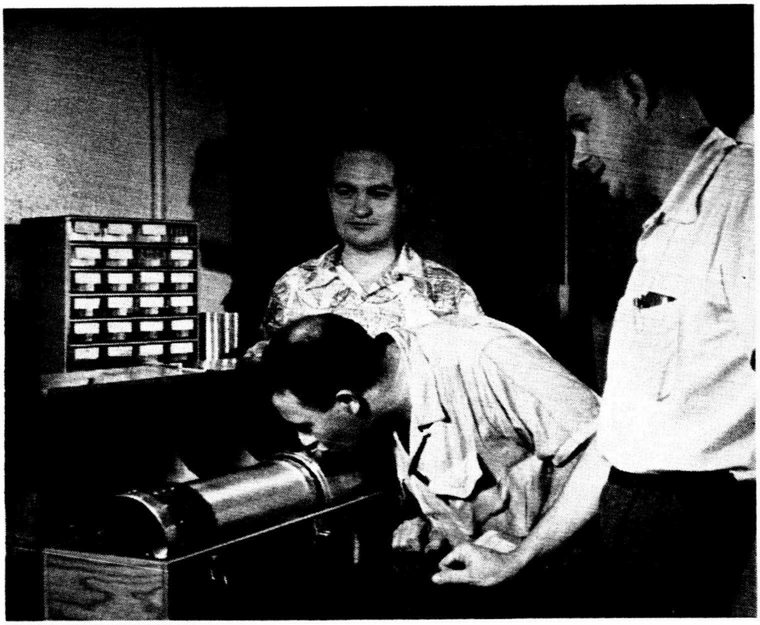
or

$$J(E_e \gtrsim 500 \text{ keV}) \approx 1 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1}.$$

Other data of Table 4 favor the second estimate, so that the scintillator is an omnidirectional rather than a directional detector in the inner zone also.

This point is very important because FARLEY and SANDERS (1962) use the detector in the outer zone to measure the *omnidirectional* intensity of particles on a magnetic shell or along a magnetic field line at L $\approx$ 3.3 and then deduce the equatorial pitch angle distribution (see RAY, 1960, and Section 2). They find a deficiency of particles with $\alpha_0 \approx 90°$ at times of magnetic quiet, a very significant finding if valid, and in conflict with the results of FAN *et al.* (1961) obtained with a different detector on the same satellite.

We consider, however, that the effect is not proven in the report of FARLEY and



The Kiss! JAMES A. VAN ALLEN expressing the sentiments of all experimenters who utilize rockets, as he farewells Explorer IV before it is taken to the launching area. VAN ALLEN, CARL MCILWAIN (left) and GEORGE LUDWIG (right) together with ERNIE RAY, were co-authors of the paper announcing the discovery of the radiation zones (VAN ALLEN *et al.* 1958). (Photo courtesy J. A. VAN ALLEN).

SANDERS (1962). Their conclusion is based on the observation that the corrected counting rate on a line of force ($L \approx 3.3$) at $\lambda \approx 0°$ is about 10% less than that at $\lambda \approx 20°$, where the counting rates were obtained by repeated crossings of the same magnetic shell (two per orbit) over a period of some eight days, from August 8 to August 16, 1959, say. They therefore require stability of the outer zone intensity to better than about 5% for eight days, during which the planetary magnetic disturbance index (K_p) varied between 1 and 6, and two days after which, the intensity increased by about 2500% (Figure 13 of ROSEN and FARLEY, 1961). In addition there are several features of the detector which do not make it optimum for such a highly discriminating experiment. Other (unpublished) measurements with the same detector are consistent with the conclusions of FARLEY and SANDERS (1962) however, (FARLEY, private communication) and the matter is so important that a more refined experiment should be carried out as soon as possible.

LUNIK I

The existence in the outer zone of appreciable fluxes of high energy ($E_e \geq 1$ MeV) electrons was deemed likely by VERNOV and CHUDAKOV (1960) on the basis of Lunik I data, and confirmed by them with Lunik II (VERNOV and CHUDAKOV, 1960b). Yet their estimate that the peak flux $j(E_e \gtrsim 25 \text{ keV}) \approx 10^9 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$ was based on the following analysis:

The energy flux in a crystal shielded by 1 g cm^{-2} of Al was 1.5×10^9 eV cm^{-2} sec^{-1} sterad^{-1}. They assumed this was all due to electrons with $E_e \gtrsim 200$ keV.

The energy flux in a crystal shielded by 1.9×10^{-3} g cm^{-2} of Al was 2×10^{11} eV cm^{-2} sec^{-1} sterad^{-1}. They assumed this was all due to electrons with $E_e \geq 50$ keV. On the assumption of a spectrum of the form $N(> E_e) \sim E_e^{-\gamma}$, they find $\gamma \approx 5$ from the above values of E and fluxes. Then, they conclude that the peak flux of electrons with $E_e \gtrsim 20$ keV was $\approx 10^9$ particles cm^{-2} sec^{-1} sterad^{-1}.

In fact, as pointed out by DESSLER (1960), if one divides the energy flux under the thin shield by an average energy of $\sim$ 50 keV, this leads to an estimate

$$j(E_e \gtrsim 50 \text{ keV}) \approx 4 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1} .$$

This is in quite reasonable agreement with currently accepted values (see Section 5).

It is actually not at all clear to us how the value $\gamma \approx 5$ was obtained. If it is accepted, and if one assumes that the thinly shielded scintillator receives all the energy of electrons with $E_e \approx 50$ keV and higher, then one would assume from the Soviet conclusions that the scintillator under 1 g cm^{-2} of Al must receive all the energy of electrons with $E_e \approx 130$ keV, since

$$\left(\frac{E_1}{E_2}\right)^{-5} = \left(\frac{50 \text{ keV}}{E_2}\right)^{-5} = \frac{2 \times 10^{11} \text{ ev}}{1.5 \times 10^9 \text{ ev}} = 130 ,$$

whence $E_2 \approx 130$ keV.

This cannot be valid, since the energy of an electron which will penetrate ≈ 1 g cm^{-2} is ≈ 2 MeV.

In fact, significant contributions to both the scintillators even in the heart of the outer zone must have come from X-rays and the penetrating electrons whose existence was confirmed by Lunik II (VERNOV and CHUDAKOV, 1960b).

LUNIK II

A combination of detectors inside Lunik II in a shield of $\sim$1 g cm^{-2} of Al still provides the best evidence for the existence of high energy ($\approx$ 1 MeV) electrons (as distinct from protons of equal penetrability) in the outer zone.

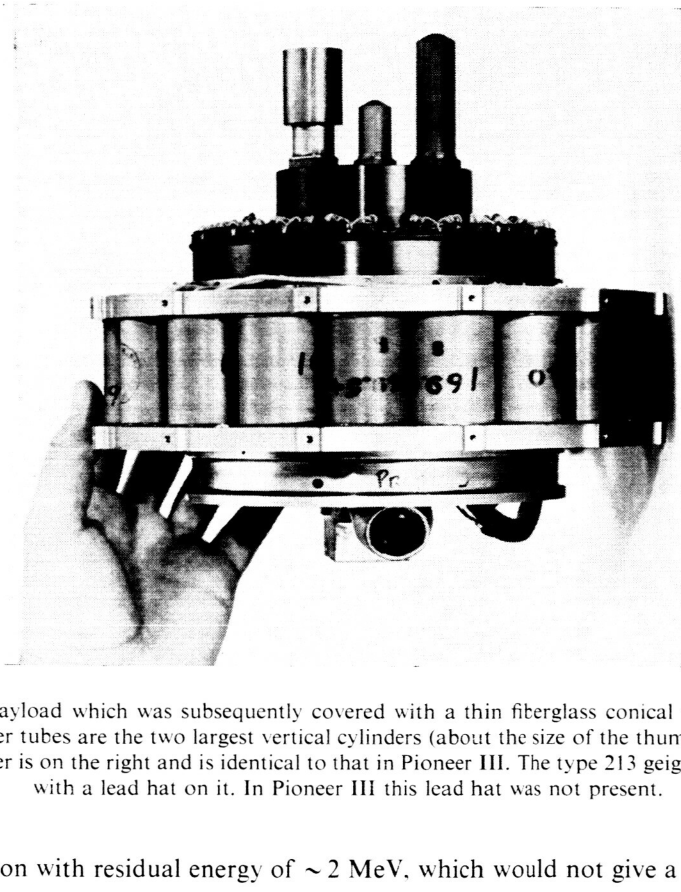
A scintillation counter inside the shield counted pulses of energy loss in the crystal of more than 3.5 MeV. This showed that in the heart of the outer zone

$$J(E_e \gtrsim 5 \text{ MeV}) \lesssim 1 \text{ cm}^{-2} \text{ sec}^{-1}$$

or

$$J(E_p \gtrsim 30 \text{ MeV}) \lesssim 1 \text{ cm}^{-2} \text{ sec}^{-1} .$$

There were two geigers inside the same shielding of ~ 1 g cm^{-2} of Al that counted at nearly the same rate. One was shielded by ~ 1.35 g cm^{-2} of Cu, equivalent to the range



Pioneer IV payload which was subsequently covered with a thin fiberglass conical thermal shield. The two geiger tubes are the two largest vertical cylinders (about the size of the thumb) on top. The type 302 geiger is on the right and is identical to that in Pioneer III. The type 213 geiger is on the left with a lead hat on it. In Pioneer III this lead hat was not present.

of an electron with residual energy of ~ 2 MeV, which would not give a count in the scintillation counter. The other geiger was shielded by 3.4 g cm^{-2} of Pb and ~ 0.3 cm^{-2} of Al, equivalent to the range of an electron with residual energy of $\approx$ 6 or 7 MeV, which could give a count in the scintillation counter. Since there were very few counts in the scintillator, and since the geiger shielded by the thinner shield counted only $\sim 10\%$ faster than the other, it was validly concluded each geiger must be detecting energetic ($\approx$ 400 keV) x-rays. This led to the estimate

$$J(1 \leq E_e \lesssim 2 \text{ MeV}) \approx 5 \times 10^5 \text{ cm}^{-2} \text{ sec}^{-1} .$$

Yet in interpretation of the Lunik III counter data there was no attempt to review the incorrect estimate from Lunik I that

$$J(E_e \gtrsim 20 \text{ keV}) \approx 10^{10} \text{ cm}^{-2} \text{ sec}^{-1} ,$$

although VERNOV and CHUDAKOV (1960b) had data which could prove that estimate to be invalid (as DESSLER (1960) showed).

EXPLORER VII

We will only consider the experiment of the Iowa group with two shielded geiger tubes (LUDWIG and WHELPLEY, 1960).

The early interpretation of outer zone data from these detectors was subject to the same potential error as data from Pioneer III and IV discussed above. Flux estimates were derived from counting rates on the assumptions that only low energy ($E_e \approx 50$ keV) electrons gave the dominant contribution by way of *Bremsstrahlung*. Both Explorer XII data (O'BRIEN *et al.*, 1962a) and Injun I data (O'BRIEN *et al.*, 1962b) show this to be invalid on occasions.

Consequently, the flux estimates of O'BRIEN and LUDWIG (1960), based explicitly on the above assumption, should be revised from between 10^8 to 10^9 particles cm^{-2} sec^{-1} downward, probably by three orders of magnitude or more. Similarly, the flux estimates of O'BRIEN *et al.* (1960) of the outer zone intensity just above a visible aurora were originally given as

$$J(E_e \gtrsim 50 \text{ keV}) \approx 10^{10} \text{ to } 10^{11} \text{ cm}^{-2} \text{ sec}^{-1} .$$

In a year's observation with Injun I the maximum flux we have seen is $J(E_e \gtrsim 40 \text{ keV}) \approx 10^9 \text{ cm}^{-2} \text{ sec}^{-1}$ (O'BRIEN and LAUGHLIN, 1962a), and we consider it probable that the above estimate over the aurora could be too high by three or more orders of magnitude. The quotation of ARNOLDY *et al.* (1962) referred to in the Explorer VI comments above, is also relevant to these two studies of particular events with Explorer VII. *The exact fluxes are completely uncertain.*

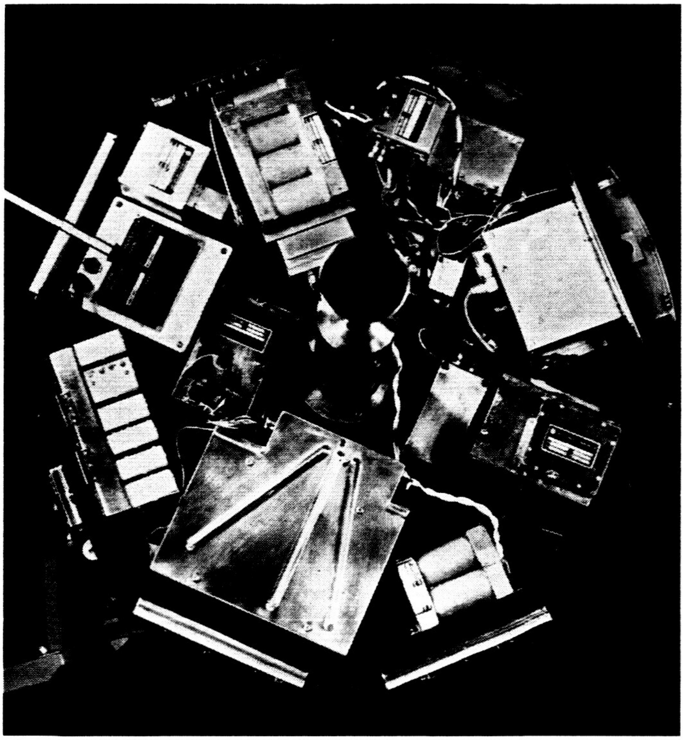
In the case of the statistical studies by VAN ALLEN and LIN (1960) and by FORBUSH *et al.* (1961), the evidence is strong that the usual particles counted by the type 302 geiger tube in the range $L \gtrsim 2$ were penetrating electrons, with energy $E_e \gtrsim 1.1$ MeV. Thus the map showing locations of peak intensity of the outer zone as being around $L \approx 3.5$ over North America (VAN ALLEN and LIN, 1960) is a map of the loci of the maximum intensity of energetic ($E_e \gtrsim 1.1$ MeV) electrons only. The corresponding map for low energy ($E_e \gtrsim 40$ keV) electrons is very different (O'BRIEN, 1962b). Furthermore, the great variations in intensity of outer zone particles reported by VAN ALLEN and LIN (1960) and FORBUSH *et al.* (1961) are probably due to a proportionately small change in the average energy of the higher energy ($E_e \approx 1$ MeV) electrons (see Pioneer III discussions above).

EXPLORER XI

The very significant measurements made with detectors on the satellite (GARMIRE, unpublished, 1962) have come to our attention only recently and in a relatively preliminary form. Therefore, we do not discuss them here.

INJUN I

The author finds it difficult to be objective about studies with Injun I, but will emphasize assumptions made (and explicitly stated) in several papers, which to his

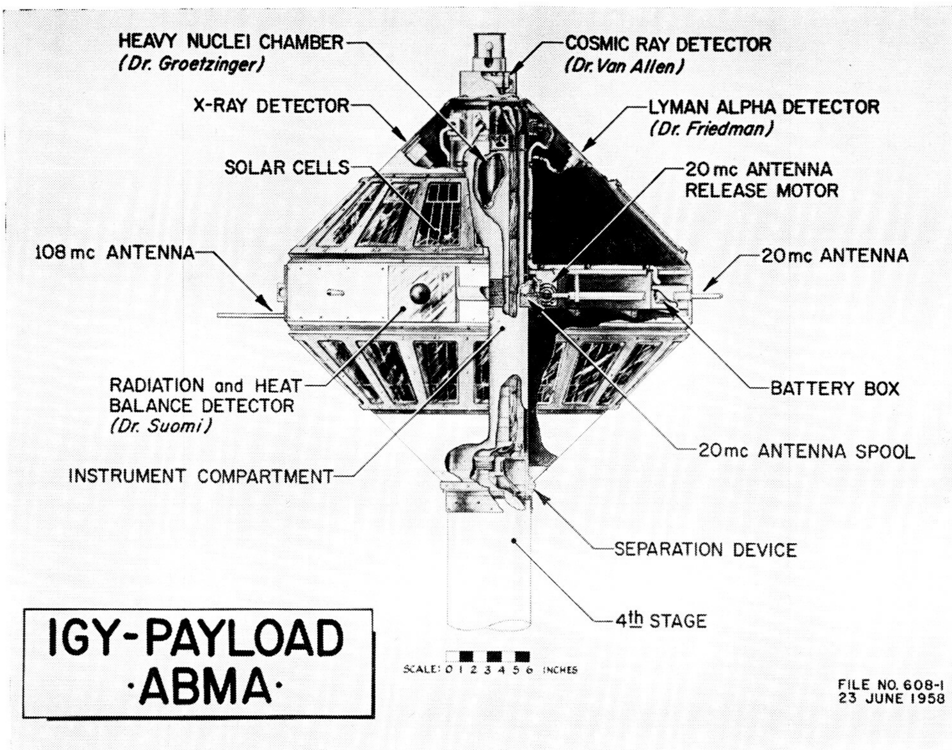


Top view of Explorer VI payload, which was 26 inches in diameter and weighed 142 pounds. The ion-chamber and geiger tube package of Minnesota are shown on left with arrow. The proportional-counter package from the University of Chicago is diagonally opposite. (Photo courtesy J. R. WINCKLER).

knowledge cannot yet be examined in any way other than treated in the respective papers.

Solar proton studies (PIEPER *et al.*, 1962) have neglected possible contributions to the counting rates of proton detectors by old, formerly trapped outer zone protons whose mirror points were lowered by the magnetic storms during which the solar protons arrived.

Studies of the precipitation of outer zone particles have been able to prove with



Sketch of the Explorer VII payload, 30 inches in diameter and weight 92 pounds. The "cosmic-ray" detector contains two geiger tubes, and it was so named at a meeting in March 1958, before the existence of the radiation zones was common knowledge. (Photo courtesy Army Ballistic Missiles Agency, Huntsville, Alabama).

other detectors that the particles in question were mostly ($\gtrsim$ 90%) electrons only if the fluxes were more than about 10^3 particles cm^{-2} sec^{-1} sterad^{-1} (O'Brien, 1962b).

Studies of the electron spectrum in the inner zone (Pizzella *et al.*, 1962b) were made with a magnetic electron spectrometer. The data are internally consistent, and consistent with results from other detectors on the same satellite, but they must be treated with care simply because the proportion of background counting rate to foreground rate is large. The main purpose of this experiment was to establish an upper limit on the flux of electrons with ($40 \leq E_e \leq 110$ keV).

The measurements of the angular distribution of electrons with $E_e \geq 40$ keV which proved that dumping occurred (O'Brien, 1962a) require a comment. The intensities in Figures 2a and 2b of that paper were normalized to the intensity in each spin through $\alpha = 90°$. Since the omnidirectional intensity varied during a spin, if (say) it increased monotonically, then if the spin was chosen from $\alpha = 180°$ through $\alpha = 90°$ to $\alpha = 0°$ the normalized intensity at $\alpha = 80°$ would be higher than the normalized intensity at $\alpha = 100°$, even if the intensity at these angles *at the one place* was the same. Thus there is some asymmetry in Figure 2b for $130° \gtrsim \alpha \gtrsim 50°$ just because of this effect, and the figure should not be used to obtain precise intensity estimates of backscattered or upward moving electrons.

MIDAS 3 AND MIDAS 4

We comment on only one feature *viz.* measurement of the intensity of protons ($E_p \gtrsim 30$ MeV) in the inner zone at high altitudes. We do not consider the spectral measurements made on these flights and a later one (SMITH *et al.*, 1962), although in order to discuss protons with energies as low as ~ 30 MeV we accept the spectral conversions from higher energies used by SMITH *et al.* (1962).

In Figure 19 SMITH *et al* (1962) compare their estimates of the intensity $J(E_p \gtrsim 30$ MeV) in the equatorial plane with those derived from Explorer IV (MCILWAIN, 1961) and Pioneer III (VAN ALLEN and FRANK, 1959a). From Midas 3 they derived a peak value $J(E_p \gtrsim 30 \text{ MeV}) \approx 10^6$ cm^{-2} sec^{-1} at $L \approx 1.5$, whereas in Midas 4 they found a peak value $J(E_p \geq 30$ MeV $\approx 8 \times 10^4$ cm^{-2} sec^{-1}. This is to be contrasted with earlier estimates of the peak to be $J(E_p \geq 30 \text{ MeV}) \approx 2 \times 10^4$ cm^{-2} sec^{-1} obtained by VAN ALLEN (1959).

SMITH *et al.* (1962) suggest that the Midas 3 flux, which was more than ten times their peak value on Midas 4 and some fifty times greater than VAN ALLEN's estimate, is a valid measurement perhaps to be explained as being correlated with intense solar proton events at the period of the flight after July 12. As justification for this suggestion, SMITH *et al.*, (1962) quote VAN ALLEN (1962) who reported that at $L \approx 1.8$ the proton intensity at $\sim$ 1000 km altitude increased by an order of magnitude following the April 1960 solar proton event. However, PIZZELLA *et al.* (1962a) show in Figure 4 that at $L \approx 1.5$ there was much less than a 30% change, and it is at this value of L, not at $L \approx 1.8$, that SMITH *et al.* (1962) found the enhanced intensity in Midas 3.

We have used Injun I measurements of the intensity of protons with $E_p \gtrsim 40$ MeV at $L = 1.5$ before and after the July 1961 solar proton events to check SMITH's hypotheses more directly. We find that if any change in the intensity of these protons at $L = 1.50$ and $B = 0.197$ gauss occurred at all, then it was again much less than a 30% change (O'BRIEN, unpublished). So we consider that the extremely high intensity of inner zone protons reported by SMITH *et al.* (1962) from the Midas 3 study must be very greatly in error. Therefore, since this error must have been in instrumental malfunction which was not detected, we hesitate to accept the findings of SMITH *et al.* (1962) from later flights, and in our summary of the known fluxes (Section 4) we used only the estimate of VAN ALLEN (1959) for the peak intensity. If the results of SMITH *et al.* (1962) from Midas 4 are valid, this estimate by VAN ALLEN (1959) should be multiplied by four. We do not regard this revision as established *at this time.*

EXPLORER XII

The only Explorer XII measurements we comment on are the preliminary ones of O'BRIEN *et al.* (1962a) aimed at settling the controversy between the estimates that the outer zone peak intensity of electrons with $E_e \geq 40$ keV was of order 10^7 to 10^8 or of order 10^{10} to 10^{11} particles cm^{-2} sec^{-1}. O'BRIEN *et al.* (1962) found that the lower fluxes were correct, and that result is still valid. However, more precise estimates of the intensities of electrons of given energies have been made since that preliminary report, and these are listed here.

ROSSER *et al.* (1962) have analyzed about ten percent of the data that will become available in due course, and they find that the time averaged value is

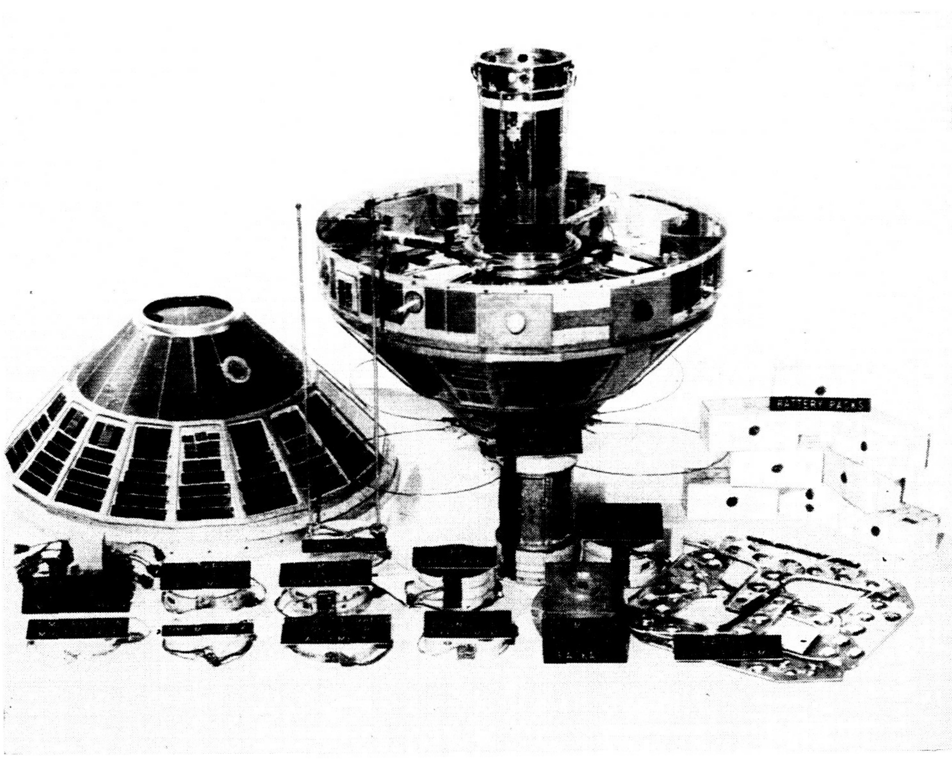
$$J(E_e \gtrsim 40 \text{ keV}) \approx 10^7 \text{ particles cm}^{-2} \text{ sec}^{-1}$$

over a wide range of $L \gtrsim 2$ in the equatorial plane. Variations of this intensity by an order of magnitude can occur with time (e.g. see O'BRIEN, 1962b).

Furthermore, in both O'BRIEN *et al.* (1962a) and ROSSER *et al.* (1962) the flux of penetrating particles is taken as

$$J(E_e \gtrsim 1.6 \text{ MeV}) \approx 10^3 \text{ to } 10^5 \text{ cm}^{-2} \text{ sec}^{-1}$$

where the variations are due to magnetic storm effects. The intensity is estimated on



Details of the Explorer VII payload. The first payload was destroyed at launch. The second was launched on October 13, 1959, and after the one-year "killer-timer" failed to act on October 13, 1960, the "cosmic-ray" package and the payload continued to operate until they gave the longest term monitoring of the radiation zones achieved to date (PIZZELLA *et al.* 1962a).

the assumption that electrons with $E_e \approx 1.6$ MeV are counted by the shielded geiger tube type 302 with essentially unity efficiency. However, 1.6 MeV is the electron energy with practical range of the geiger shielding, and electrons with just this energy are counted with only $\sim 10\%$ efficiency. So the above estimates should be multiplied by perhaps a factor of ten if the same energy threshold (1.6 MeV) is considered (VAN ALLEN, private communication).

Lack of knowledge of the electron spectrum in the critical interval of 1 MeV $\leq E_e \leq 3$ MeV had led us to avoid explicitly making such an uncertain correction.

8. Associated Measurements

8.1 GENERAL

In the preceding discussions, those measurements of the radiation zones made with rocket-borne apparatus have been included since they have given information essential in seeking interpretation of satellite studies. In the following, a few key references to other measurements of associated phenomena are listed briefly.

8.2 SATELLITE-BORNE EXPERIMENTS

Measurements of solar plasma in interplanetary space by BRIDGE *et al.* (1962) with Explorer XI and by GRINGAUZ *et al.* (1961b) may be considered as measuring an input for the radiation zone.

Measurements with a magnetometer on board the same satellite as the particle detectors can be of particular assistance in the interpretation of temporal variations of the particle radiation (e.g., see ROSEN and FARLEY, 1960; CAHILL and AMAZEEN, 1962). A magnetometer may also be used as a sensor with which to measure the pitch angles of detected particles.

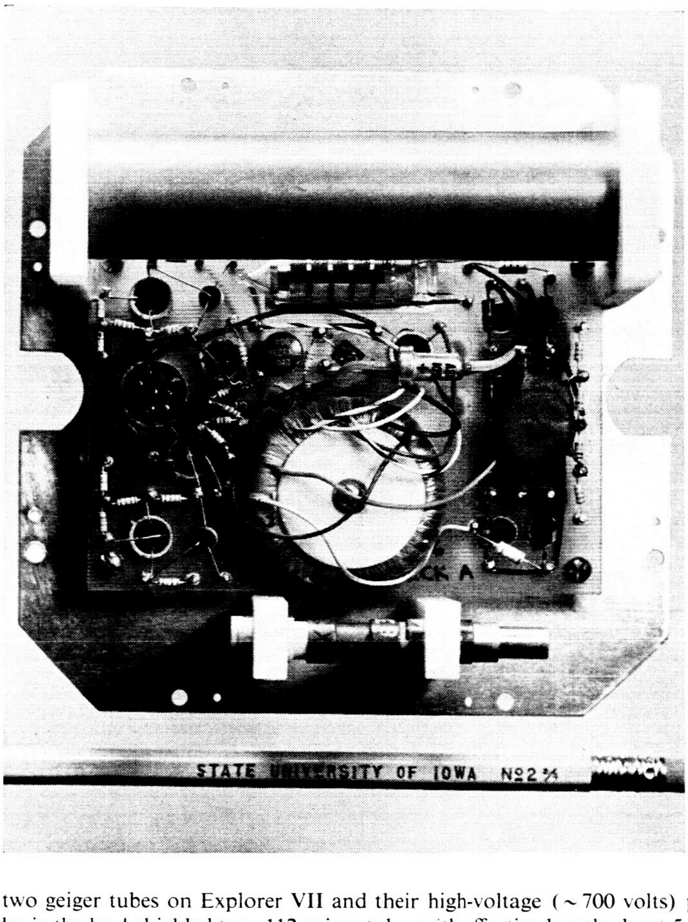
Several experiments primarily intended to measure other phenomena on satellites have been affected by particles of the radiation zones. While in many cases the result has been simply undesirable contamination, in other cases there is the possibility of obtaining useful data about the radiation zones. In this second category are included:

(a) The solar X-ray experiment on Explorer VII (T. CHUBB, private communication);
(b) The heavy-primary cosmic radiation experiment on Explorer VII (POMERANTZ *et al.*, 1961); and
(c) The astronomical γ-ray telescope on Explorer XI (GARMIRE, 1962, unpublished).

8.3 GROUND-BASED EXPERIMENTS

Extremely extensive observations of electrons precipitated into the atmosphere have been made with balloon-borne detectors (ANDERSON and ENEMARK, 1961; WINCKLER, 1960). Rocket studies have been made of protons and electrons in aurorae (e.g., MCILWAIN, 1960a) and of particle outflux in magnetically quiet periods at mid and high latitudes (IVANOF-KHOLODNY, 1962). Such experiments have unique value in investigating possible relations between the radiation zones and atmospheric and ionospheric effects, which we do not discuss here.

Similar effects can be studied, for example, by ground based observations of auroras, radio absorption, etc. The detection of synchrotron radiation from high energy electrons spiralling in the geomagnetic field was formerly impractical because there were insufficient intensities of high energy ($>$ 1 MeV) electrons trapped at low



Detail of the two geiger tubes on Explorer VII and their high-voltage (~ 700 volts) power supply. The top cylinder is the lead-shielded type 112 geiger tube, with effective length about 5 cm. The lower tube is the geiger type 302, with effective length about 1 cm (LUDWIG and WHELPLEY, 1960). (Photo courtesy W. A. WHELPLEY)

altitudes, so that the cosmic noise was much larger than the synchrotron emission from naturally trapped electrons (DYCE and NAKADA, 1959). With the creation of the artificial radiation belt on July 9, 1962, the signal-to-noise ratio (or, if one prefers, the noise-to-signal ratio!) is so large that the synchrotron emission is readily detectable at low magnetic latitudes, and it is a means of following the time decay of intensity in the belt (HESS, private communication).

9. Some Requirements for an Ideal Experiment

9.1 GENERAL

It is not our intention to write at length about the requirements which we consider should be met in an experiment purporting to add significantly to knowledge of the radiation zones. These requirements are mostly obvious ones to take account of the new environment in which the measurements will be made, and include those procedures usually adopted in careful experimental work. We therefore merely list a few of the requirements, and do not discuss them. Some of them may appear to be self-evident, but reference back to Section 7 will make it apparent that they are not.

As discussed in Section 2, the objective of a definitive experiment is either to obtain

Description A

$$j_i\,(L, \alpha_0, E)$$

or *Description B*

$$J_i\,(L, B, E)\,.$$

When we speak of an experiment, this may of course include as many detectors as necessary.

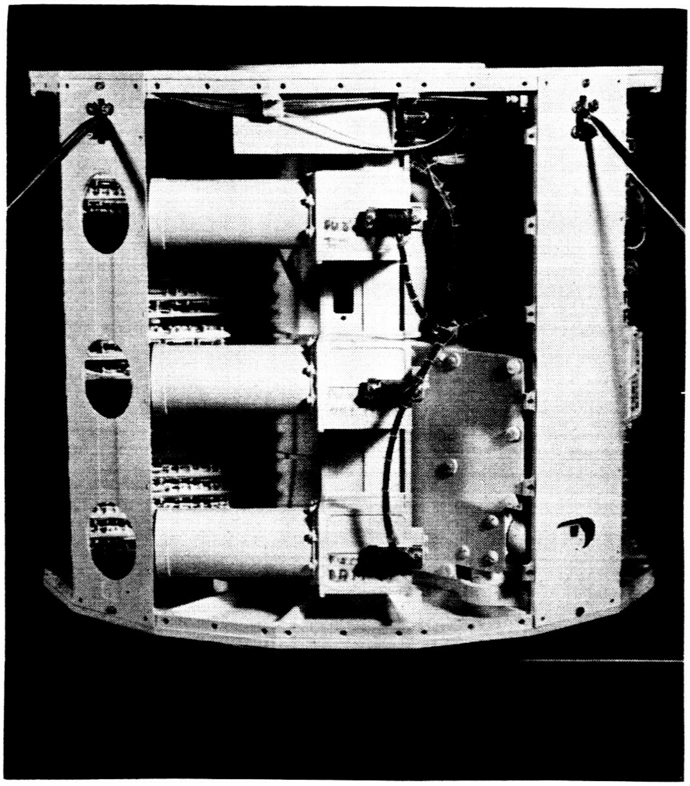
9.2 SCIENTIFIC DESIGN

In obtaining spectral discrimination in the radiation zones, there is a greater need to cover a wide range of particle energies than there is to obtain fine spectral resolution (e.g., see Figure 6). All spectra known to us except that of inner-zone protons at $E_p \lesssim 100$ MeV vary monotonically, and energy resolution of

$$\Delta E_n \text{ at } E_0, 2\,E_0, 4\,E_0 \quad 2^n\,E_0 \ldots (n = 0, 1, 2 \ldots)$$

where $\Delta E_n \approx 0.2 \times 2^n\,E_0$ would appear to be quite adequate. The value of n should be as large as possible, and E_0 as small as possible. For example, in studying outer zone electrons and their temporal and spatial variations, values of $E_0 = 1$ keV and $n = 13$ would be sufficient to cover the range of interest, but would not be more than sufficient.

In obtaining temporal or spatial resolution, the requirements are clearly a function of L. Also, since a low altitude satellite moves at some 8 km/sec, spatial and temporal resolution are clearly not independent. For $L < 2$, temporal variations are slow (PIZZELLA *et al.*, 1962a), but steady state spatial variations are large (MCILWAIN, 1961; YOSHIDA *et al.*, 1960). For example, temporal changes are presumably small in an hour (e.g., see Figures 4 and 5 of PIZZELLA *et al.*, 1962a), but the particle intensity can change by a factor of ten over an altitude change of only 100 kilometers (e.g., Figure 2 of YOSHIDA *et al.*, 1960). For $2 \leq L \lesssim 4$, the spatial changes and temporal changes compete in a satellite. For example, see Figure 2 of FORBUSH *et al.* (1961) and Figure 9 of CLADIS *et al.* (1961) which show about a factor of 2 or 3 change in intensity of electrons per 100 km change in altitude at altitudes of 1000 kilometers or less. Significant temporal changes can certainly occur in a few seconds during magnetic disturbances. For $L \gtrsim 4$, i.e., in those regions commonly subject to auroral influences, altitude is not as dominant a spatial parameter as is latitude (or L), and neither spatial nor temporal resolution has yet proved adequate in satellite studies. Judging from measured widths of auroras (AKASOFU, private communication) one would expect

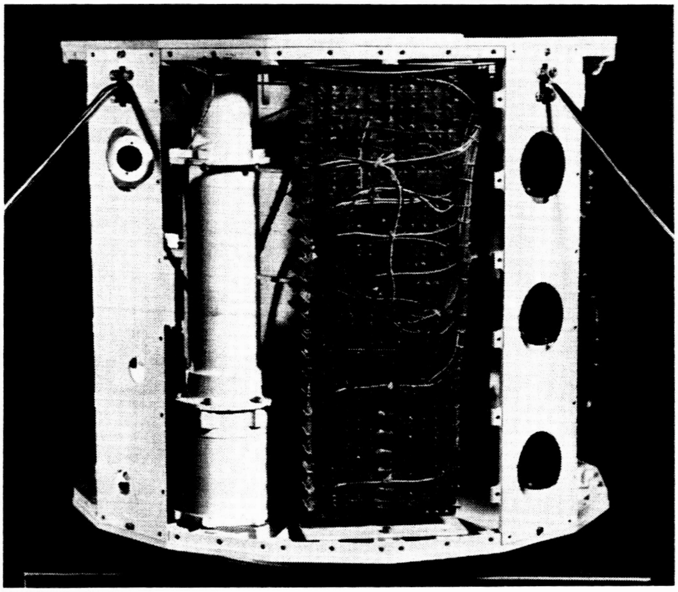


Side view of the Injun I payload, which was 16 inches high and 13 inches diameter, and weighed 40 lbs. The three detectors shown one above the other with viewing apertures on the left, were three cadmium sulphide detectors. The detector at right near the bottom with a small aperture visible is the p-n junction detector package (see Table I).

spatial variations over ~ 100 meters or less at altitudes of ≈ 1000 kilometers (where the radius of gyration of a 10 keV electron is ~ 10 meters). A satellite will traverse such a distance in ~ 10 milliseconds. Also, since variations in electron intensity of more than one thousand in less than one second (or 8 kilometers) and of one million in about thirty seconds (or 200 kilometers) have been seen with Injun I (e.g., Figure 1 of O'BRIEN and LAUGHLIN, 1962a) it is apparent that high resolution telemetry (≈ 10 milliseconds) is necessary in satellite studies of intense events in the outer zone. One probably needs balloon-borne apparatus under the satellite so as to distinguish spatial from temporal effects.

It is apparent that in general, measurement of only two types of particles, *viz.*, protons and electrons, will suffice. However, special experiments to study other particles, e.g., positrons (CLINE *et al.*, 1962) should be performed.

In obtaining Description A, the coverage and resolution in L and α_0 are so dependent on the vehicle characteristics, *viz.*, apogee, perigee, spin rate or stabilization



Side view of Injun I, rotated 90° with respect to the Photo on page 474. The three apertures visible on left are fromtop to bottom, that of the open-ended geiger type 213, and the two (smaller) apertures of the electron spectrometer. The three apertures on the right are those of the cadmium sulphides detectors seen in the Photo on page 474 side-on. The vertical column at left is the auroralphotometer, which viewed out the top. It is now blocked by the Greb satellite. A permanent magnet in the payload has its axis parallel to the photometer and therefore perpendicular to the detectors whose apertures are shown. One half of the data-encoding electronics is shown.

technique and so on, that we do not discuss them. We similarly avoid discussion of the desired coverage in L and B for Description B.

We might comment in this context of scientific design that we are assuming that a more complete description of the particle radiation is essential before its origin can be understood. The experimentalist suffers greatly from lack of guidance as to what measurements are meaningful to the theoretician, particularly in outer zone and auroral studies. It may well be that the phenomena at $L \gtrsim 6$ are so greatly disorganized that the experimentalist who designs the ideal experiment will fail to find any particular feature common from event to event. Such a discovery would be valuable of itself, if somewhat frustrating.

9.3 TECHNICAL DESIGN

The requirements for good geometry and clean shielding are apparent. If, for example, a directional detector is designed, it is apparent that it is desirable to have most of the detected radiation entering it honestly. It is also generally desirable to provide a background detector even when one obtains good geometry.

The dynamic range of any detector should be at least over four decades of intensity and preferably over six or more. We know of no satellite orbit within the radiation zones where the intensity of any particle type of a given energy will vary by less than a factor of one thousand. The resolution of intensity need be generally only a few percent.

Indeed, one may use the variations in sensitivity due to the temperature and voltage dependence of the detector as setting an upper limit to the desired resolution. The combined effect of the expected variations in temperature and voltage should never exceed about a 10% variation in the detector sensitivity. There are standard techniques for minimizing these effects (e.g., see McIlwain, 1960b; Ludwig, 1960; Josias, 1960; and Enemark, 1959).

It is of course essential that the final flight unit itself be calibrated with standard sources over a range of environmental conditions considerably in excess of those expected in flight. In many units, the sensitivity to changes in supply voltage or temperature is greatest in the region where there is a significant difference between apparent and true counting rates, and of course the unit must be activated to such rates in environmental testing. The problems of pile-up of small pulses being such as to trigger a discriminator are now very great in the region $L \lesssim 1.5$ (Section 6) but we do not attempt to deal with such detailed technical problems here.

Designing and preparing the detector to withstand the shock and vibrations of launching also are fairly standard procedures (e.g., see Ludwig, 1960).

All these matters and a number of others have been discussed, for example, by Ludwig (1960), Josias (1960), and McIlwain (1960b). Other useful and comprehensive references are Brini *et al.* (1961) who display many electronic circuits, Bloom *et al.* (1960), Davis and Williamson (1962), Fairstein (1961), and Friedland *et al.* (1962).

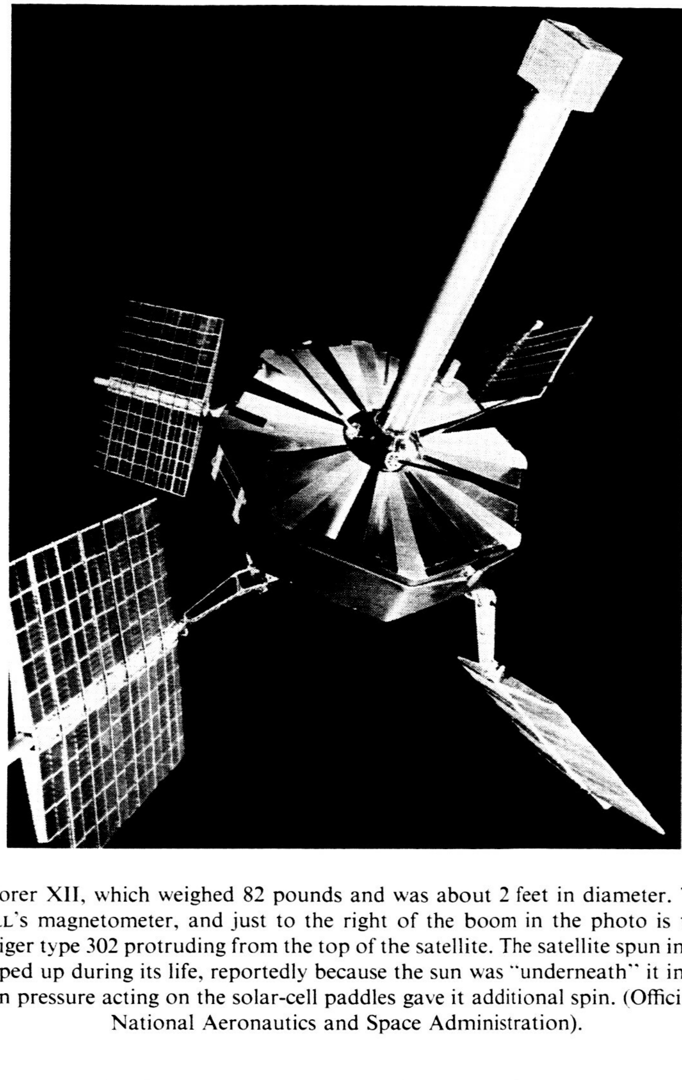
Considerations of payload design to satisfy requirements of radiation zone experiments are too complex to discuss here. We merely mention two techniques of value:

(1) Orienting the payload with respect to **B** (e.g., see Fischell, 1961) since the trapped radiation flux is cylindrically symmetric about **B**; and

(2) Cooling the payload to $\sim 0°$ C so as to improve greatly (by one or more orders of magnitude) the signal to noise ratio in photomultipliers and other devices whose threshold of detectability is limited by thermionic emission.

9.4 TELEMETRY ENCODING AND DECODING

The role of data transmission and analysis is extremely important in satellite studies of the radiation zones. Whereas normally with experiments in the laboratory, data are completely analyzed only when the experimental set-up is perfected (if the experiment is controllable and reproducible) or when an event of particular interest occurs (for example, in geophysical non-controllable and non-reproducible experiments), in many satellite studies of the radiation zones all the data *may* be of importance.

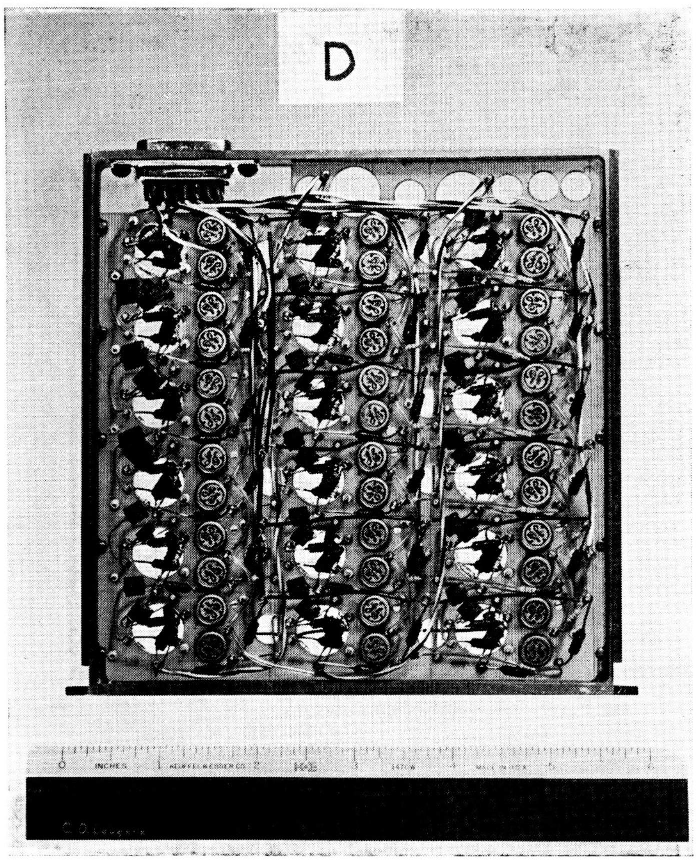


View of Explorer XII, which weighed 82 pounds and was about 2 feet in diameter. The boom-box houses CAHILL's magnetometer, and just to the right of the boom in the photo is the SUI omni-directional geiger type 302 protruding from the top of the satellite. The satellite spun initially at about 30 rpm, but sped up during its life, reportedly because the sun was "underneath" it in this view, and solar radiation pressure acting on the solar-cell paddles gave it additional spin. (Official photo of the National Aeronautics and Space Administration).

As a consequence, the data must be so organized that they can be scanned visually and yet analyzed rapidly. Clearly a computer is essential finally. Yet in any exploratory experiment one does not know which questions to ask the computer, so visual inspection of data is also necessary.

The amount of data acquired by a satellite can be enormous. The experience of the State University of Iowa in this regard is of interest. With Explorer I, there were some five thousand measurements; with Explorer IV, about forty thousand; with Explorer VII, about one million; and with Injun I, about fifty million (and Injun I is still operating!).

The logistics of the data reception, decoding and analysis then may become a very



One deck of the SUI data encoder on Explorer XII, with eighteen stages of binary scaling. The deck is about 5.5 inches in width (Compare with photo on page 436).

great problem unless they are planned during the very design of the satellite itself. The transmission of data from the satellite should be so designed as to simplify decoding on the ground and efficient transfer of the decoded information to a computer. With the Injun series of satellites we allocate about 25% of the payload weight to on-board encoding and computing so as to minimize the number of bits which convey the information about the counting rate of a detector, so as to send the data in binary form which can be decoded easily on the ground, so as to provide parity-check information with which a computer can reject noisy data, so as to provide an on-board frame counter which uniquely labels every segment of data supplied to the computer without introducing any human interface, and so on.

In the early satellite experiments, the encoding was such that much of the decoding had to be done by hand. Consequently, for example, reduction of the forty thousand data points from Explorer IV from two months' flight required eighteen months' hand reduction by some ten personnel. Reduction of the Injun I fifty million data points on the other hand, is kept up to date with some ten people and one IBM 7070 computer for some five hours each day!

To summarize this section, we hold firmly to the opinion that the experimentalist must regard the matter of data encoding and analysis as among his prime responsibilities when planning an experiment. He cannot afford to wait until the payload is in orbit before he becomes organized.

9.5 POSSIBLE CONTAMINATION OF RADIATION-ZONE EXPERIMENTS

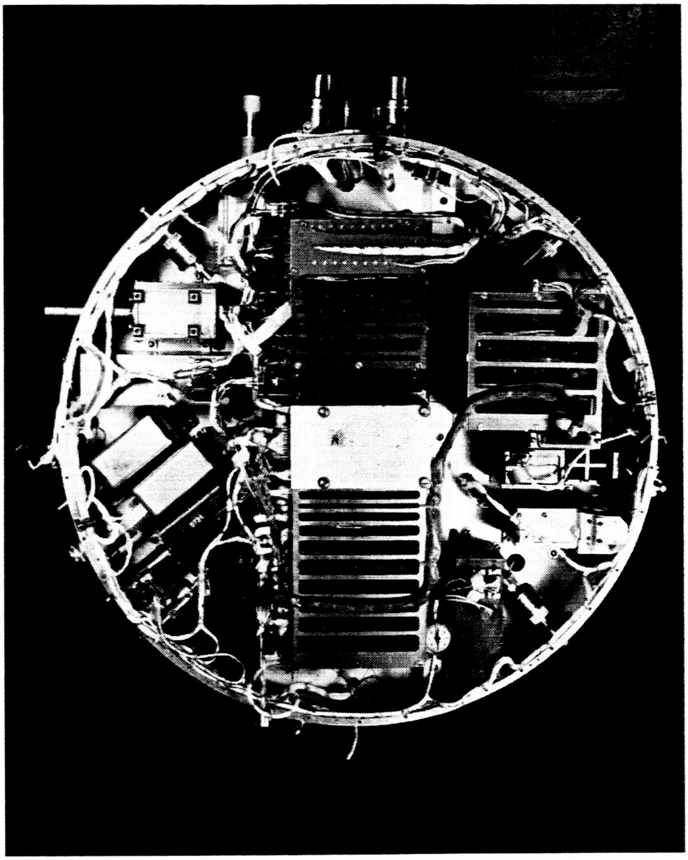
Besides those malfunctions of detectors due to drift in gain, or increase in noise, and so on, there are natural phenomena which can erroneously indicate the presence of trapped particles. There is the obvious problem of earthlight, sunlight, etc., affecting light-sensitive detectors. Since the solar flux is about 10^6 ergs cm^{-2} sec^{-1}, if a scintillator is being used to measure low-energy electrons, for example, then there must be an attenuation of sunlight by 10^9 in order to measure electron fluxes of interest. Similarly, the sun can emit $\sim 10^6$ X-rays cm^{-2} sec^{-1} of about 1 keV energy in a typical flare (CHUBB *et al.*, 1962) and such detectors as a thin-windowed geiger tube can count at significant rates under such a bombardment. Other possible contaminations even of shielded detectors are cosmic-ray protons and heavy nuclei in fluxes of ≈ 2 cm^{-2} sec^{-1}, and solar protons (at $L \gtrsim 3$) in intensities as high as $J(E_p \gtrsim 30\text{ MeV}) \approx 10^4$ cm^{-2} sec^{-1} (LIN, 1961). The fluxes of cosmic-ray electrons $j(E_e \gtrsim 500\text{ MeV}) \approx 5 \times 10^{-3}$ cm^{-2} sec^{-1} sterad^{-1} (EARL, 1962) and $j\ (100\text{ MeV} \leq E_e \lesssim 1300\text{ MeV}) \approx 5 \times 10^{-3}$ cm^{-2} sec^{-1} sterad^{-1} (MEYER and VOGT, 1962) are too low to be of concern generally.

10. Conclusions

Experimental studies of the radiation zones have been subject to the same imperfections as most other experimental physics, with some extra problems because of the features peculiar to rocket and satellite work. We consider that the theoretical physicists must review the existing knowledge, and suggest specific experiments which would be of particular significance. The theoretical studies of radiation-zone phenomena are so new that the theoretician can start essentially afresh, without being fettered by theories based more on longevity than veracity. We trust that this critical review of experimental work may be of value in such efforts.

The following quotation from MARITAIN (1959) is so apt to this paper that it will serve as a conclusion:

"The intellect . . . is no longer interested in anything but the invention of apparatus to capture phenomena – conceptual nets that give the mind a certain practical dominion over nature, coupled with a deceptive understanding of it; . . . by advancing in this fashion, not by linking new truths to already acquired truths, but by substituting new apparatus for outmoded apparatus; by handling things without under-



Top view of Injun III satellite, not yet launched as of October, 1962. Regarding this as the face of a clock, the following detectors are seen: at 12 o'clock, a type 302 geiger tube and two auroral photometers; at 3 o'clock a low-energy differential electron spectrometer and a high-energy integral electron spectrometer; at 6 o'clock (just to the right of the compass) a p-n junction proton telescope, and, proceeding clockwise still, another auroral photometer and a high-energy proton scintillator; at 7:40 o'clock, an open-ended geiger, an electron multiplier and a d-c scintillator; at 9 o'clock, two open-ended geigers and a p-n junction proton telescope. The permanent magnet to orient the payload along **B** from 6 o'clock to 12 o'clock is the long rectangular bar under the magnetic compass at 6 o'clock. The payload is 24 inches in diameter.

standing them; by gaining ground against the real bit by bit, patiently, through victories that are always piecemeal and provisory – by acquiring a secret taste for the matter with which it conspires – thus has the modern intellect developed within this lower order of demiurgy a kind of manifold and marvellously specialized touch as well as wonderful instincts for the chase."

Acknowledgements

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